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SPECIAL Radio Communication

Volume 10
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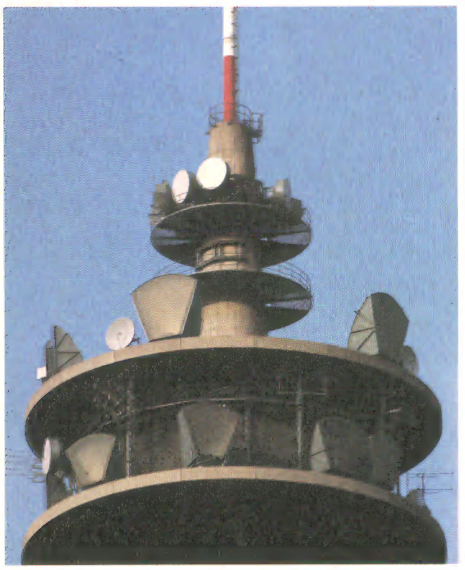

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Radio relay links are a crucial part of today's communication networks. Modern techniques provide the high capacity needed to support the transmission of television, telephone, mobile telephone and data traffic

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Dear Reader

"Radio Communication" concludes a four part series of telcom report Specials on topics from the field of radio communication. This special issue focuses on radio relay technology and is supplemented by chapters on power supplies, project engineering, components technology and quality assurance. Though primarily applicable to radio relay, the supplementary chapters, including the foreword and introduction, are relevant for all four volumes. Comprising this series of Specials are:

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Foreword

The special issues of "telcom report" from the field of telecommunication transmission – 1979 "Digital Transmission" and 1983 "Optical Communications" – have met with a very favorable response from the readers. The current issue continues this series with the treatment of radio communication. The present time seems to be particularly well suited to this purpose, since a range of innovations have produced a new impetus for "Radio Communication."

Thus in radio relay the changeover to digital transmission resulted in the introduction of new systems which, inter alia, are making a substantial contribution to the rapid construction and extension of the long-haul networks between the digital switching centers. Wide-area coverage cellular networks with a capacity of several hundred thousand subscribers are currently being established for mobile radio communication. By employing modern technology, these networks are able to offer considerably greater user convenience than previous networks. In addition to the established satellite communication systems for international telephone and television links, increasing use is being made of systems providing national and regional coverage. Such systems, for instance, allow commercial users rapid and flexible access to "new services" within the framework of the Integrated Services Digital Network (ISDN). New technologies have also led to considerable progress in the field of special radio networks for strategic and tactical purposes.

As this special issue shows, development engineers in all these fields have produced solutions which will be able to meet the telecommunication requirements of the next decade. This issue is not merely a presentation of the newly-developed transmission equipment, but – beyond this – it is intended to familiarize the reader with the fundamental solutions we have produced in important areas, such as quality assurance, the use of new technologies and project engineering.

May this present special issue experience the same reception as that accorded to the previous publications.

Dr.-Ing. Rudolf Herz

Head of the Transmission Systems Division in the Telecommunication Networks and Security Systems Group of Siemens AG, Munich

Heinrich Keil and Friedrich Künemund

Development Trends in Radio Communication

Establishing communication links rapidly has always been a province of radio communication; after all, only transmitting and receiving equipment is required for the purpose. The atmosphere assumes the role of the transmission lines otherwise necessary. For many PTTs the most interesting aspect is the possibility of multipath and multimedia transmission, as well as the ability to bridge difficult terrain with large repeater spacings. In particular, its rapid exploitability will make radio communication a pace setter in the future also and, as in the past, this will necessitate intensive development of ever newer system concepts as well as improved or even new techniques and technologies. This applies equally to radio relay, satellite communication and mobile communication.

The use of digital signal processing is gaining increasing importance in all areas of radio communication. As a consequence, inhibiting factors such as the finite usable frequency range and the effect of the weather and terrain formation on the radio path can be progressively counteracted. This can be achieved by the use of adaptive equalizers in the time domain and error-correcting coding which can also facilitate operation in substantially higher radio frequency ranges. Coding to prevent unwanted "listening-in" is also made possible by digital techniques.

The developments indicated above are becoming attractive particularly as a consequence of the progress in large-scale integration of the ever-growing digital circuits (**Fig. 1**). An important part is played in this context by the current-saving CMOS technology and the

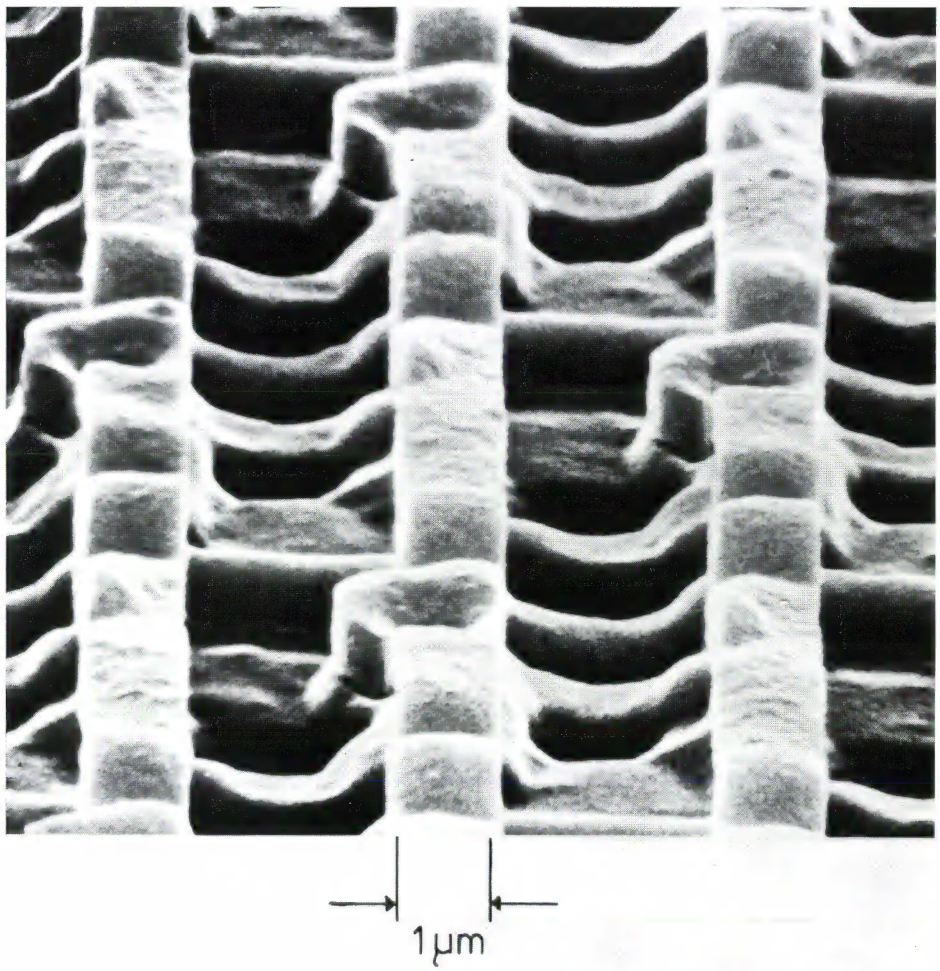

Fig. 1 Large-scale integration permits economic production of digital circuits. A section of a CMOS chip is shown

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Fig. 2 Shell-type antenna for orthogonal polarization mounted on a tower platform

high-speed bipolar technology. Large-scale integration is possible and also necessary, particularly due to the continued improvement in operating reliability that is aimed at with simultaneous increasing circuit complexity. In addition, further reductions in current drain and space requirements are obtained in this way, together with the possibility of more economic solutions. Coming "technological advances" already indicate improvements in these characteristics, thus further confirming the selected route – the development of digital systems. Optimum operational use of the transmission equipment cannot be achieved without the use of integrated digital circuits for the logic functions in the protection switching and supervisory control equipment.

This again emphasizes the extent to which progress in the development of radio systems is determined by progress in semiconductor technology and techniques. It is not limited to digital signal processing and logic functions in baseband modules, protection switching and supervisory control equipment, but also concerns analog and digital circuits in intermediate and radio frequency ranges. Thus fast divider circuits for carrier supplies on the basis of silicon and gallium arsenide are being used at ever higher frequencies in radio systems. The same applies to the use of gallium arsenide semiconductors for analog applications in the signal path, such as low-noise preamplifiers and power amplifiers, as well as integrated intermediate frequency amplifiers.

The increasing importance of software development – above all for optimizing the use of radio systems – must also be mentioned. This calls for more and more distributed "intelligence" in the systems and thus the interoperation of increasing numbers of computers and processors.

The increasing complexity of signal and logic procedures in the systems make it absolutely essential to assure the reliability of hardware and software in the future by means of a more systematic approach. Increasing use of computers and automation of the test sequences are currently among the most important measures [1].

Turnkey transmission network projects are gaining increasing importance. Extensive experience in project management and a broad range of products are required for this purpose, which in turn are among the particular strengths of Siemens [2].

Radio relay is already substantially digital

In the development of radio relay systems particular emphasis will be placed on broadband digital systems for long-haul traffic as well as for short-haul and local traffic, in addition to narrowband systems for local traffic and for special networks [3, 4]. Multilevel modulation methods (up to 256 QAM, quadrature amplitude modulation) are being developed for medium-term use in long-haul systems up to about 13 GHz in order to transmit higher bit rates (e.g. 2 × 140 Mbit/s or even 4 × 140 Mbit/s) with maximum economy of bandwidth and high efficiency. This no doubt applies also to broadband systems above 13 GHz in the long term. Nevertheless, in the medium term rapid and economic realization is more important than frequency economy in these systems in order to be able to interconnect digital switching centers in cities, for instance, or to extend long-haul routes into cities. Systems with low transmission capacity (up to 34 Mbit/s) preferably use frequency bands below 3 GHz and above 13 GHz. Applications as distribution systems (point-to-multipoint) [5] with a time-division multiple access method (TDMA) can already be discerned, e.g. for the connection of several small

groups of subscribers to the national network.

The fact that digital signals can be regenerated means that there is no theoretical limit to the cascading of hops. As a consequence, it becomes possible to establish short-haul networks with hop lengths less than 10 km and to use for this purpose frequency ranges lying at about 20 GHz. This becomes particularly appropriate if it is possible to make the radio relay systems more cost effective.

However, the efforts to reduce costs are not restricted merely to the utilization of large-scale integration [6, 7] and optimization of system usage with extended use of service channels [8, 9]. Development is continuing on the use of surface acoustic waves for filters and oscillators in the intermediate frequency range [10, 11], on hybrid and monolithic integrated microwave circuits [12, 13] with distributed and concentrated circuit elements, as well as on dielectric resonators [14, 15] for filters and oscillators in the radio frequency range. In this context mention should also be made of the further improvement in diversity techniques, as well as the double utilization of the radio frequency range (frequency reuse) by means of orthogonal polarization. Great importance is likewise attached to the further development of transmitting and receiving antennas (**Fig. 2**) which, in addition to orthogonally polarized waves, can also be used in at least two radio relay frequency bands [16, 17, 18]. This permits the operating company to save not only the expense of further antennas, but also antenna mounting space in radio stations, which may possibly make it unnecessary to make a structural change to a radio relay tower or even build a new one.

In the final analysis, the development of combined solar and wind energy sources for the operation of radio relay stations is likewise aimed at reducing costs for the operating company [19]. However, minimizing the equipment power consumption by means of circuit integration using CMOS and gallium arsenid technologies is a prerequisite in this case also (**Fig. 3**).

Fig. 3 Radio relay station in Oman powered by wind and solar energy with a passive cooling system

Satellite communication offers "New Services"

In scarcely any other field of telecommunication transmission have so many system proposals and interrelated ideas for solutions to problems been published as in the case of satellite communication. On the one hand they are aimed at making the applications realized so far more attractive, and on the other at extending the circle of users by means of new systems and applications. In this connection the extent to which the transmission systems can be adapted to the wishes of the various users (bandwidth, transmission time or bit rate, outlay in the earth station) plays an important part.

The principal applications consist of links over very large distances (e.g. Intelsat, **Fig. 4**) and also with mobile subscribers (e.g. Inmarsat) as well as the distribution of information (e.g. DBS) including the distribution within small regions (e.g. TV-Sat) [20, 21]. The rapid establishment of generally medium bandwidth communication links to remote areas (rural technologies, Glodom) as well as for large companies, such as banks, hotel chains, insurance companies, news agencies, industry etc. with their branches (e.g. via communication satellite SBS, IBS, DFS, ECS-SMS) is also a major application. Especially high growth rates are being predicted for the domestic systems, e.g. with broadcast, rural and business applications within a region or country.

Among the new services, mention can be made here of video conferencing, the expanded international television program exchange and the support of mobile radio networks by means of satellite systems. Links to regions of the

Fig. 4 Intelsat antenna system in Burum (Netherlands)

earth lying in the extreme north and south can be realized by means of satellites with extreme elliptical orbits (non-geostationary), as proposed in the Loopus system [22].

In order to perform the multitude of tasks particular attention must be paid to improving the orbit utilization – in particular the utilization of the synchronous belt. This is certainly a matter of ever increasing concern in satellite communication.

An important step in this direction was taken with the introduction of digital technology. With the aid of the demand assigned TDMA (DA-TDMA) method, it is now possible to conserve bandwidth by assigning transmission capacity to the user as required [23]. Mention should also be made of the introduction of digital speech interpolation (DSI). These new techniques can also be realized with some of the earth stations installed by Siemens (Standard A, C-Band, 4/6 GHz) [24]. It is true that the introduction of these methods is only just beginning, but their further development can be confidently predicted. A reduction of the bit rate per voice channel to 32 or 16 kbit/s, as well as methods of video compression to further reduce the bandwidth requirement are the aims of development plans.

Further measurements to improve orbit utilization are still in the development and planning phases. The main emphasis of the various activities corresponds roughly to the following list:

- utilization of Ka band (20/30 GHz) and increased use of Ku band (11/14 and 12/14 GHz) with the additional advantage of smaller antenna dimensions,
- antennas with improved sidelobe suppression permit reduced orbit spacings. Offset antennas as well as the use of conformal phased array (CPA) antennas which can be adapted to the satellite structure and whose beam direction can also be varied electronically are pointers to the future,
- use of each of the antennas for at least two frequency bands,
- concentration of several antennas on one antenna platform.

The use of Ka and Ku bands simplifies operation with small earth stations (antenna diameter 1 to 5 m), such as are preferred for domestic systems. In addition, further means of shifting the outlay from the earth station to the satellite are being developed or planned:

- energy concentration by means of small zones of illumination on the earth surface (spot beams), permitting frequency reuse within large regions;
- rapid switching of the message stream from one beam to another in order to connect subscribers of differing regions in spite of small zones of illumination (SS-TDMA);
- where necessary beam scanning in order to illuminate large areas of the earth in spite of small zones of illumination (energy concentration);
- a further increase in the output power of the transponders will be made possible by means of more efficient solar cells, e.g. on the basis of gallium arsenide;
- regeneration of the digital signals in the satellite transponder;
- improved satellite position stabilization in order to make antenna tracking in the earth station unnecessary even with somewhat larger antennas.

These are some of the known proposals aimed at reducing the outlay for the user. Further known proposals are aimed at solving specific problems. Their realization probably lies in the more distant future:

- the use of multilevel digital modulation methods (e.g. 16 QAM and higher) to reduce bandwidth,
- performance of switching functions in the satellite,

- direct link between satellites (cables in the sky) in order to avoid the roundabout route via an earth station,
- a platform flying at intermediate altitude and acting as an active or passive relay station (space mirror), whose position is stabilized with the aid of microwave energy radiated from the earth.

After this list of future-oriented projects, mention should be made of the current position of satellite communication in the Federal Republic of Germany. Here the domestic system "Deutsches Fernmeldesatelliten-System" (DFS) [24 to 27] with the satellite Kopernikus is currently being developed by a group of companies. In addition to Siemens as the leader, the consortium includes ANT Nachrichtentechnik GmbH, Standard Elektrik Lorenz AG, as well as Messerschmitt-Bölkow-Blohm GmbH/ ERNO Raumfahrttechnik GmbH.

Deutsche Telepost Consulting GmbH (DETECON) together with the Deutsche Bundespost, the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V. (DFVLR) (German aeronautics and space research institute) and the consortium have worked out the system concept. The tasks of the DFS system include:

- the distribution of television programs, including live TV reporting from variable locations,
- the expansion of telephone and data traffic with Berlin (West), and
- the creation of a special network for business traffic including video conferencing.

Both the Ku band and the Ka band will be used in the system which will also employ spot beams. These comments are intended to draw attention to the fact that, although ambitious, the system concept is realistically based on the latest findings and is oriented to demand.

Fig. 5 User handset for the C450 modile radio system

Mobile radio systems are also going digital

Market research indicates that about 100 times more mobile radio telephones than hitherto could be sold if their price were on the order of that of a first-class car radio – provided the infrastructure to deal with this flood of traffic existed. It is above all the constantly increasing ability of industry to integrate circuits on a large scale, particularly for digital signals, that makes it appear possible that such prices will be approached. Therefore, it is not surprising that a high growth rate is predicted for mobile radio systems.

In the subscriber equipment of the recently commissioned cellular FDMA mobile radio networks (FDMA frequency division multiple access), PLMN (public land mobile network) microprocessors have already been incorporated for digital logic functions such as radio channel selection and supervision (**Fig. 5**). In the Deutsche Bundespost's mobile radio network C, specially developed large-scale integrated circuits are even being used. This is a first step aimed at increasing the cost effectiveness and thus making it more economic for the user.

The speech signal is transmitted in analog form over the radio path of the Deutsche Bundespost's mobile radio network C and only converted to a digital signal in the transceiver equipments, in order to be able to employ digital integrated circuits for its processing in the baseband. A substantially larger step towards the price concept referred to will only become possible with digital transmission of the speech signal over the radio path. This will require bandwidth saving coding and modulation methods. Digital signal transmission results in further advantages, in particular the possibility of encoding, the integration of voice and data as well as adap-

tive radio channel optimization. As a result of the extensive use of large-scale integration, the units are becoming smaller and require less power for operation. As a consequence, the mobile telephone will become even easier to use in the form of a portable telephone.

Worldwide all companies active in the field are working on the next generation of the cellular system. In the Federal Republic of Germany, for instance, Standard Elektrik Lorenz AG is developing a broadband digital system concept employing TDMA, such as has been realized in principle in the Intelsat system, for instance. This basically makes the occasional assignment of large bit rates, and also access to the Integrated Services Digital Network (ISDN) possible. Technical advantages over narrowband systems are claimed for this broadband TDMA transmission, and these are primarily realized by means of adaptive optimization of the radio channels.

Of the proposals for new cellular systems announced so far, mention should be made here of the TDMA narrowband method and the frequency hopping method in addition to the FDMA narrowband and TDMA broadband systems already referred to. But first of all the biggest task to be performed and the one that is most important for the future of mobile radio systems is the specification of the system most suitable for European conditions. The radio frequency band assigned for this purpose will lie at about 900 MHz.

An European organization consisting of committees from industries involved in switching (EUCATEL) and transmission (ECREEA) – the task force mobile services (TMS) together with the group special mobile (GSM), an organization of the European postal administration CEPT (Conférence Européenne des Administrations des Postes et des Télécommunicationes) – has taken on this task and aims to work out the specifications by 1988.

The decision to be taken between the TDMA and the FDMA proposals calls for more development work and investigation, particularly regarding the economic consequences for the user. A valuable basis for the further development of mobile radio systems at Siemens is the know-how acquired during the production and commissioning of the C450 mobile radio system in the Deutsche Bundespost network [28].

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Günther Fink, Bernt Köttgen and Edwin Wolf

Radio Communication – an Innovative Market

Telecommunication transmission systems are of great importance in all spheres of life. Without a rapid and secure exchange of information, the continued flourishing of the industrialized countries cannot be assured nor is the economic development and the improvement of the living conditions in industrializing and developing countries conceivable. Even in the private sphere, life without the global services, such as telephony, television and radio broadcasting, cannot be imagined. In the years to come the attractiveness of telecommunication transmission will be further enhanced by improved and new services. It is thus no wonder that above-average growth rates in these market segments are also predicted for the future.

Either cable systems or radio systems are nowadays employed for the transmission of information by electrical means. Which of these transmission media is used is determined by factors such as cost-effectiveness, topography, and security. However, its special characteristics ensure an important role for radio communication.

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From the wide field of radio communication, the following sections of this special issue address themselves to the sectors satellite communication, radio relay, mobile radio systems and special-purpose networks. These sectors occupy secure positions in the overall field of telecommunication transmission and thus participate in its growth – albeit to differing extents.

Radio relay

In common with other forms of telecommunication transmission, radio relay systems have profited from the large increase in the need for communication. This applies particularly to the demand for telephony. In addition, the demand for TV transmission, sound program transmission and, more recently, data transmission also must not be overlooked, particularly in view of the fact that for decades TV transmission has been the exclusive domain of radio relay (**Fig. 1**).

A new impetus was provided by the decision of many PTTs to convert their existing analog networks to digital operation. This triggered off far-reaching new developments in all areas of telecommunication transmission and thus, naturally, in radio relay also. With the aim of completely replacing analog technology in about 15 to 20 years, the following tasks have been set for radio relay, in part jointly with cable transmission systems:

- Conversion of the long-haul network to interconnect the digital trunk exchanges,
- Opening up of frequency ranges up to 30 GHz for the (increased) use of radio relay systems in the short-haul network,
- Increased use in the local network,
- Replacement of the present analog TV and sound-program channel network,
- Program feeding and distribution to TV transmitters and CATV headends,
- Development of facilities for protection switching and supervision.

The provision of nationwide broadband communication networks is planned in many countries and the first trial installations are already in operation. This will provide further impetus to radio relay development and require the solution of additional demanding problems, particularly relating to frequency planning and frequency-band utilization. By providing solutions roughly comparable in cost-effectiveness to those of its "cable competitor," radio relay will be able to maintain, and perhaps even extend, its position in the transmission networks. Considerations of *multipath* and *multimedia transmission*, which are vital for high-quality, secure transmission networks, will retain their validity and favor the continued use of radio relay systems.

Further opportunities for radio relay systems arise in cases where it is necessary to provide suitable short-term links, for instance for new private program providers or for users who have decided at short notice that they wish to participate in ISDN communication. Even during the construction of an optical cable backbone network, rapid recourse will be made to radio relay systems in order to overcome bottlenecks in the long-haul network, or to make feeder links available at short notice in the short-haul and local networks. In the product definition phase of radio relay systems, it is necessary to consider not only the

Fig. 1 Television tower for the radiation of TV and sound broadcast programs and for radio relay transmission

purely technical requirements, but also the economic aspects, operational experience and the possibility of use in international markets.

Product development guided by such considerations has also brought success for Siemens in foreign markets. The topography of many countries together with the maintenance facilities available there mean that frequently there is no practical alternative to radio relay systems, when a terrestrial transmission medium is required.

Whereas PTTs and other customers in industrialized countries have large numbers of highly specialized staff for network planning, the planning and construction of the infrastructure, as well as for maintenance and operation, such services frequently have to be provided by the equipment manufacturer in other countries, and are then a condition for the award of a contract. Siemens is geared to such requirements and has the know-how necessary to perform this kind of planning for the customer and to complete turnkey projects. It is able to offer suitable project management and to assure future operation by means of intensive training of customers' staff and maintenance contracts.

In addition to the transmission systems, such turnkey projects also require the provision of suitable power supply systems and shelters, which are optimized on the one hand for the requirements of the telecommunication equipment and on the other for the environmental condition of the particular country or the equipment installation site. In this connection the requirements for simplicity and minimum maintenance cost can be taken for granted. The long-term aspects of the operating costs also play an important part in the selection of a suitable solution. The outlay for the purely radio equipment may sometimes fade into the background in comparison with the outlay for the infrastructure.

Suitable antenna and protection-switching designs are also of considerable importance in the assessment of a proposal. "Radio communication systems from a single source" with all peripheral equipment and a suitable infrastructure is certainly not merely a slogan in this context, but rather a prerequisite for an optimum technical and economical solution.

Fig. 2 The new earth station in Fuchsstadt (Permit No. 30913, Luftbild Bertram)

Satellite communication

The international organization Intelsat stationed the first synchronous satellite "Early Bird" over the Atlantic in 1965 for *intercontinental telecommunication via satellite*. By means of this relay station in geostationary orbit, a new radio link with hitherto unobtainable capacity, transmission quality and availability was inaugurated between the USA and Europe, in addition to the conventional shortwave radio.

As early as 1964, the Deutsche Bundespost commissioned one of the first three European earth stations in Raisting, in southern Bavaria. Since the first synchronous satellite only permitted single carrier operation, the earth stations in Raisting, Goonhilly (England) and Pleumeur-Bodou (France) took weekly turns at communicating with the American station in Andover (USA).

As prime contractor, Siemens was entrusted with the construction of the station in Raisting and may thus consider itself a pioneer in this field.

Intelsat now operates a total of 16 synchronous satellites over the Atlantic, Indian and Pacific oceans, to which worldwide more than 800 earth stations have access. Whereas "Early Bird" (Intelsat I) had a transmission capacity of only 240 voice channels, Intelsat VI will soon offer a capacity of 30,000 voice channels and three TV channels.

The expansion of the Intelsat system to 16 satellites with ever-improved technical characteristics and continually expanded transmission capacities, and its use for intercontinental, regional and mobile applications, all within a period of 20 years, is proof of the spectacular development of satellite communication with annual growth rates of considerably more than 10%.

Siemens has also participated in the remarkable development of satellite communication. In the Federal Republic of Germany there are currently installed at Raisting and Fuchsstadt alone (**Fig. 2**) a total of seven Intelsat Standard A earth stations with antenna diameters between 25 and 32 m, which are used for intercontinental telecommunication. Siemens was the prime contractor in the construction of all seven stations. With this background, Siemens was able to compete successfully for further Intelsat stations in the international market. Examples of these are Burum in the Netherlands, Ras Al Khaimah in the United Arab Emirates, as well as Honduras.

In parallel with the intercontinental links via Intelsat satellites, *regional satellite systems* have been developed in recent years to provide communication links for regional or national areas. For instance, Eutelsat, to which 20 Euro-

Fig. 3 User equipment in a mobile station for the Deutsche Bundespost mobile radio network C

pean PTTs belong, operates the satellites Eutelsat I-F1 and Eutelsat I-F2 for Europe. Whereas satellite I-F1 now additionally distributes TV programs from various European countries to broadband cable systems, satellite I-F2 provides modern communication links for business users. It is intended to facilitate new services, such as videoconferencing, rapid data transmission between computers, remote printing of newspapers, high-speed facsimile and teletex transmission throughout Europe.

Siemens was also awarded a contract for the supply of 15 earth stations to be used for this modern form of business communication via the satellite I-F2. With antenna diameters of 4.2 m and 5.6 m, these stations have been in service since 1986, and offer channels for data rates between 64 kbit/s and 2 Mbit/s. In addition, with a similar equipment configuration, they are suitable for intercontinental business communication via Intelsat satellites.

The PTTs of our European neighbors are likewise preparing for business communication via the satellites operated by Eutelsat and Intelsat.

France with its satellite system Telcom I and the Federal Republic of Germany with the German communication satellite system (DFS) are the outriders for purely *national satellite systems* in Europe. These systems are also intended mainly for business communication and TV program distribution.

The Deutsche Bundespost gave the task of producing the German communication satellite system to a consortium comprising Siemens, ANT, MBB/ERNO and SEL, with Siemens assuming the leadership. It is to be hoped that with this system the Deutsche Bundespost has provided a model for a series of domestic satellite systems which are in the discussion stage worldwide. The system is intended to be ready for use in 1988 and, in addition to the services already mentioned, it will facilitate the testing and use of frequencies in the 20/30-GHz band which have not yet been used for satellite communication in Europe.

In many countries, it is anticipated that the market for business communication via small satellite earth stations will gain considerable importance in the coming years.

As a company with a comprehensive product spectrum for telecommunication transmission, Siemens intends to participate in the future not only in the market for Intelsat stations but also in the growth market for business communication via satellites – Siemens is well prepared for this too.

Public mobile radio

The public mobile radio service in the Federal Republic of Germany has its origin in the year 1950. Introduced at that time as the "Public land mobile radio service," it commenced operation with manual connection of calls. Between 1950 and 1970 this service experienced an annual increase in the number of users in excess of 25%. In the end about 27,000 mobile users were served by the "B2 network."

By the mid-seventies it became obvious that the existing equipment would not be able to meet the requirements of the future. On the one hand, the number of users was limited by the available frequencies and by the system concept to about 25,000; on the other hand the possibility of considerable improvement became very apparent. In addition to this, the increasing mobility and rising standard of living of the population made a radical expansion of communication for mobile users necessary.

The planning performed towards the end of the seventies and the groundwork in related fields made it possible for Siemens to respond to the Deutsche Bundespost's invitation to bid with the offer of a future-oriented system, which makes extremely economic use of frequencies and which exhibits the improved quality of service for user and system operator already referred to.

Trial operation of the network set up with the Siemens C450 mobile radio system commenced on September 1, 1985. Unrestricted operation commenced on May 1, 1986, with substantially wide-area coverage right from the start. The Deutsche Bundespost has thus put into service what is probably the most modern system in the world serving mobile radio users.

This network is structured as a cellular system, i.e. a system which allows the formation of cells with small radius and automatic call handoff between cells. With these characteristics, reuse of the frequencies at small intervals is possible, and thus also the ability to serve a large number of users. One feature of this system which is worthy of special mention

is the distance measurement employed for detecting the cell boundaries. This is necessary for effective cell formation and is a feature not offered by other cellular systems. Automatic abbreviated dialing, speech scrambling to prevent undesired listening-in and magnetic card authorization are further examples of the numerous advantages offered to the users.

With this system, the Deutsche Bundespost will be able to support at least 300,000 users by the beginning of the nineties, i.e. times as many as hitherto in the B2 network.

In addition to providing the infrastructure, Siemens is involved in numerous markets as one of the leading suppliers of user equipment (radiotelephones) designed to meet specific national standards (**Fig. 3**). This allows comparison of the capabilities of differing concepts, and the specific national requirements can be incorporated in current development work.

Predictions are frequently overtaken by events, and this will apply to the number of mobile users when the convenience of use, investment costs for mobile stations and user charges are correctly related to each other.

This trend will be aided by the ability to remove the mobile station from the car and to use it as a truly portable unit which can be taken everywhere.

Thus, in the long term, it can be assumed that the number of "mobile" stations will rise to a substantial percentage of the fixed main stations. For the moment this prediction applies mainly to the highly industrialized countries and means that not only business users but also a large number of private users will participate in this service.

A further frequency band is necessary in order to cope with the predictable growth. The 900 MHz band is to be used for this purpose in the future.

In addition to extending the capacity, the aim here is to produce a uniform European system which permits cross-border user traffic. Furthermore, this system should be suitable for the anticipated increase in data communication and extend the digitization of the fixed network out to the mobile user.

The standardization activities of the European PTTS are aimed at this goal; industry is preparing for this new generation which will offer the user even more advantages and convenience and thus promote the extension of this service.

Special purpose networks

For the most part HF (high frequency) radio uses the shortwave band. It has developed from the older form of wireless communication, and has experienced rapid growth since its beginnings at around the turn of the century.

With the introduction of submarine cable and satellite links at the beginning of the sixties, it appeared at first that HF radio had been superseded, since satellite links offer substantially better channels capacities and transmission quality than HF radio links. In spite of submarine cable links and today's communication between continents via satellites, HF radio has remained the bearer of continental and intercontinental communication links, e.g. for maritime and aeronautical services, maritime news service, for links to meteorological offices and embassies etc. In addition, there is a series of national HF radio services which are largely operated by security services and the military. In this area there has been a perceptible increase in the teleprinter and data traffic, particularly via small radio stations, as a result of their exceptional cost-effectiveness and the automation of HF radio links.

The present state of the art offers secure data transmission via HF radio up to 2400 bit/s. Intelligent communication processors in conjunction with HF radio transceivers today allow the setting-up of a connection via an HF radio link by means of automatic channel selection, so that the preparation by the operator to establish an HF radio link now largely belong to the past. Frequency management and mode of operation are stored in the equipment, and the link is established by means of a start command, as in the case of public telex traffic.

Data protection procedures ensure error-free message transmission. Interference-resistant transmission which is secure against listening-in is nowadays an important requirement in these communication networks. This is achieved by encoding the information, as well as by the use of frequency hopping techniques and burst transmission.

Radio relay links in conjunction with "digital" switching equipment are basic elements for wide-area, multi-channel message transmission in special purpose networks also. For this purpose Siemens developed the CTM 200 modular digital radio relay system, which takes into account all requirements of mobile use (**Fig. 4**). The ability to completely control the system remotely meets all the requirements for operation in modern, computer-controlled communication networks (network management).

Summary and outlook

In summary, it can be said that radio communication will respond to the challenge presented by new tasks and the increased demands made by our modern communication society and will work out suitable solutions.

In the field of radio relay, the trend to optimum utilization of the available frequency bands and the drive to use higher frequency ranges will continue in the course of the conversion to digital systems. Moreover, in the future, radio relay will retain its importance for multipath transmission in the long-haul network as an economic alternative to cable, and will gain an increased foothold for short-haul traffic as well as in local networks.

In satellite communication, regional and national systems particularly for both the new public services and for broadcasting will have good future prospects. Here also the opening-up of higher frequency ranges is a pressing task. In addition, the proven Intelsat systems will maintain their outstanding significance for intercontinental telecommunication transmission by the use of satellites with ever-greater performance and modern sequential access methods.

Public mobile radio will present an interesting market in view of the potentially high number of users. Rising user convenience of the equipment offered, as well as falling investment and operating costs (charges) for the user equipment, will assist mobile radio in acquiring a rapidly expanding group of users, and

Fig. 4 Microprocessor controlled CTM 200 radio relay system in mobile application

usage will then soon extend beyond that for purely business purposes.

HF radio links will retain their position in the spectrum of possible links. They now ensure secure communication transmission for fixed and mobile services, are independent of political boundaries and are very cost-effective. It has been possible to reduce the dimensions of the products to a handy size by means of a high level of component integration. Furthermore, new technical solutions are aimed at making HF radio links even more secure, particularly against listening-in and message interception and against disturbance of existing links by interference sources. With the development of a family of new HF transceivers, together with an HF communication processor, Siemens has set new standards and produced an HF communication system, which can be employed in many areas and which already meets many of the military and commercial requirements of the future.

In conclusion, a word about quality. All development, production and sales activities would be jeopardized, if the equipment and systems supplied did not exhibit the degree of reliability required in operation. In order to attain and ensure this long-term reliability, a quality assurance system is necessary which is effective in *all* phases of product genesis, and which is organizationally independent of the departments making the product.

Siemens has a mature quality assurance system of this nature. It extends from the extremely careful selection of components and materials (and their internal conformity testing) via reliability tests to prescribed standards at various development stages through to the definition of production methods, receiving inspection and the extensive testing of the end products themselves. Conformance with legal and technical specifications, with safety requirements and standards is likewise part of the quality assurance system, as is also the continuous *verification* of conformance.

It is known that customers are paying increasing attention to the criterion, "quality," since the technology is getting more complex and the associated equipment more expensive, but operation should remain simple and easily comprehensible. In this field, Siemens occupies a good position internationally which will be maintained and expanded.

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Munich Radio Production Facility – Modern Production Methods Assure High Quality

The series production of radio systems for commercial telecommunications in many respects makes special demands on production methods, material procurement and quality assurance. This results from the production engineering requirements of modules for ever higher frequencies, the high reliability demands and the widely diversified product spectrum [1]. The methods employed in the Munich radio production facility for the large-scale production of sophisticated high technology systems and equipment are described below.

In the 60,000 m^2 Munich radio production facility (**Fig. 1**) 2700 employees currently work some 2.5 million production hours annually. In addition to 1900 craftsmen, 800 staff are concerned with process planning, progress monitoring, quality assurance and administration.

Production is concentrated on radio relay systems for analog and digital signal transmission in public and private telecommunication networks, together with transmission equipment for earth stations and for mobile radio systems.

Bringing together on schedule the large number of individual components and subassemblies for the roughly 2000 end products necessitates the use of extensive data processing procedures. With their help all administrative processes, starting from the breakdown of the sales orders into individual components, scheduling and monitoring the timely

Fig. 1 Radio relay systems and transmission equipment for satellites and mobile systems are manufactured in the Munich radio production facility

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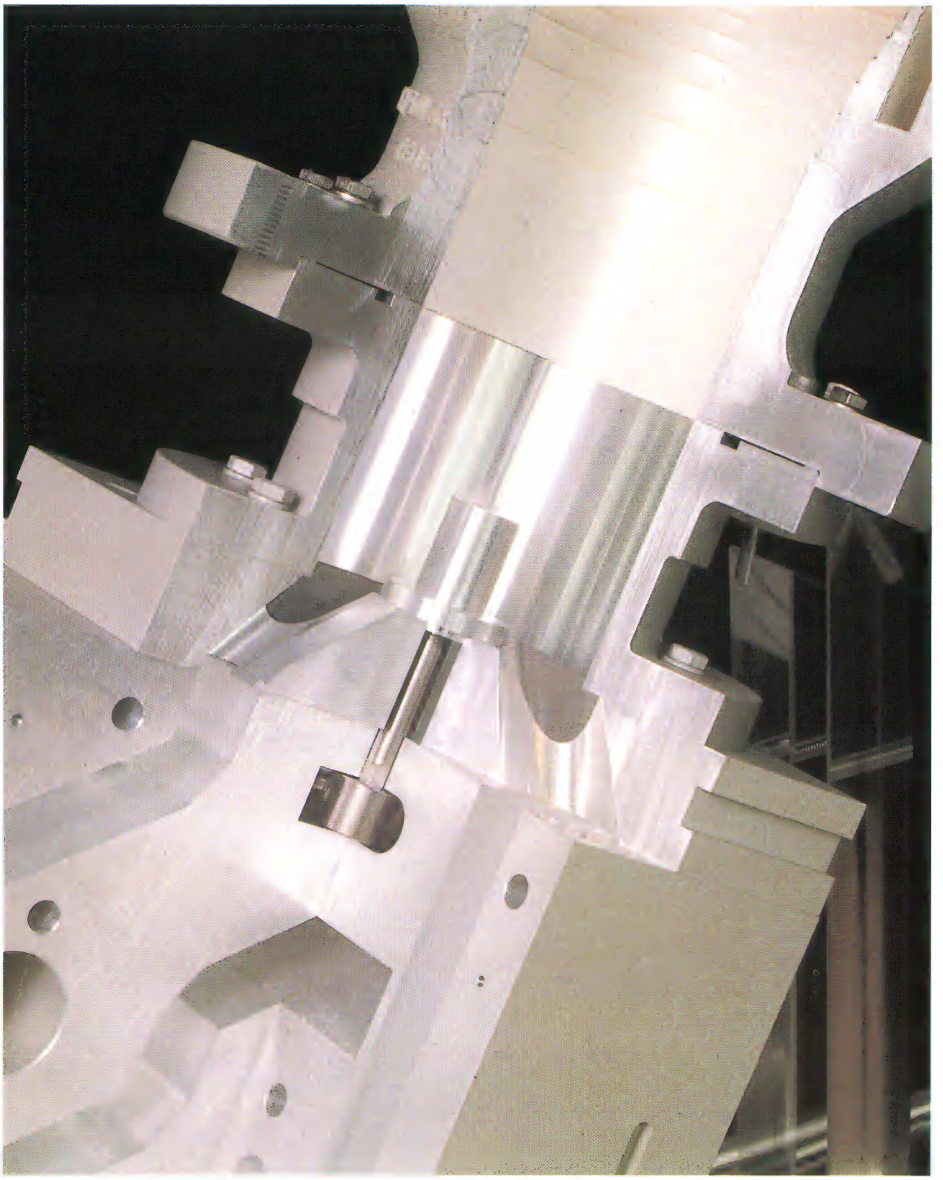

Fig. 2 Antenna feed system with double waveguide T-junction produced on an NC milling center, opened up to show the interior

delivery of these components through to storage control, costing and charging for work done, are performed largely automatically.

The product spectrum and the complex technology in high frequency bands (1 to 30 GHz) call for the closest cooperation between production and the development departments located at the same site.

The principal operations involved in the production of radio relay equipment with particular emphasis on production techniques are presented below. The aspects of quality assurance and electrical testing are described in a separate article [2].

Procurement

Some 100,000 different parts and subassemblies are required for the radio relay equipment spectrum alone. Of these, 60,000 are produced and assembled by in-house workshops and 40,000 are procured externally. A typical radio relay equipment (transmitter) incorporates about 1200 electrical and mechanical parts. A multitude of parts and components must therefore be available on schedule in the radio relay production facility. For this reason, an order processing center with integrated purchasing function coordinates all external and internal procurement operations, and ensures timely availability while taking into account economic aspects. Due to its complexity, this task can only be performed with the aid of data processing facilities. For this reason, all organizational procedures in the radio production center – from the identification of secondary requirements through procurement and stocking, as well as the timely provision of sets of parts for production lots – are controlled by data processors. A dedicated data processing system with 150 terminals is available for this purpose.

Microwave semiconductors and integrated circuits occupy an important position in procurement, and are the subject of special procedures. For highly specialized components in complex technology, sample approval is necessary in many cases before release for delivery.

Fabrication of mechanical parts

The microwave components used in radio relay systems, such as oscillators, converters, amplifiers and filters, require highly accurate mechanical parts for faultless operation (**Fig. 2**). In addition to the accuracy (typical tolerance 0.03 mm), the surface roughness and the absolute freedom from burrs, particular demands are placed on the production methods by the great variety of special materials employed, e.g. Invar, quartz, ceramic, ferrites and Teflon. Production takes place exclusively on nummerically controlled, and in some cases linked machines, in order to minimize the effect of the operator. Programmable NC automatic testers ensure objective results during quality control also. The NC machines are programmed at graphics workstations, which receive the necessary geometrical data from a development data bank.

The following are a few examples of the high technological level obtained in mechanical fabrication:

- flexible manufacturing cells for milled parts with automatic change of tool and workpiece (250 different tools), making a production tolerance of less than 5 µm possible;
- deburring milled microwave components by thermal deburrer. Complete removal of burrs – while retaining sharp, rectangular corners – is a prerequisite for the correct operation of microwave equipments;

- vacuum soldering chamber for aluminum for producing complicated waveguide components (e.g. waveguide transitions),
- process controlled automatic plating baths for the production of silver, nickel, copper and zinc layers of defined thickness and high corrosion resistance,
- plating baths with additional facilities for silver plating interiors (internal electrodes),
- robot controlled automatic welder (plasma positive electrode) for the economic production of hermetically sealed or RF shielded cases and equipment cases.

Careful process planning for each individual part is necessary in order to ensure that the required accuracy of reproduction is maintained in the series.

The technical procedures to be employed in each production step are defined during process planning. The process sheet is then generated by logical and optimized stringing together of the individual procedures. This process sheet describes the path of a part or a subassembly through the workshops and, in addition to the technical procedures, contains details of the special tools and the qualification of the workshop personnel. Generation of the process sheet including the program for the numerically controlled machines takes place with computer assistance at special workstations (**Fig. 3**).

Fig. 3 Workstation for computer aided process sheet generation including program generation for NC machines

Assembly

The assembly of radio relay equipment is subdivided into preassembly, module assembly and equipment assembly. Preassembly, for instance, refers to the production of subassemblies for microwave modules, such as circulators, isolators and film circuits. The most varied bonding and soldering methods (reflow or vapor phase) are used for this purpose.

This all takes place under clean room conditions or under laminar flow, as does also the subsequent mounting of the microwave semiconductors. Intermediate storage of the components takes place in nitrogen-filled containers (**Fig. 4**).

The preassembly and assembly of microwave modules calls for highly qualified personnel, and is therefore per-

Fig. 4 Temporary storage of microwave modules in nitrogen-filled containers in the assembly shop

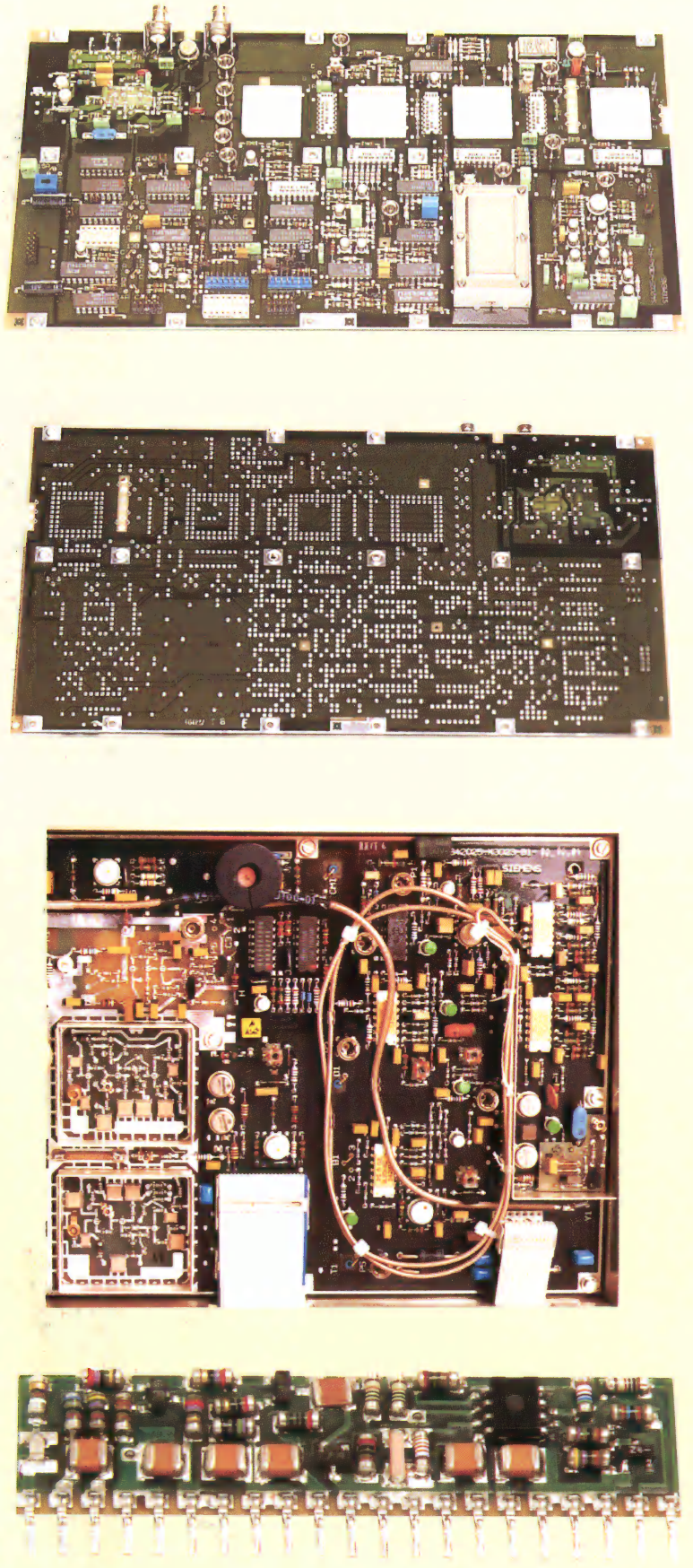

Fig. 5 Printed-circuit assemblies before and after the soldering process

formed exclusively by experienced craftsmen.

Production of the printed-circuit assemblies takes place in parallel with the assembly of the microwave modules. The bending and cropping of component leads as well as control of the soldering processes are to the fore at this stage (**Fig. 5**). Components and PC boards are therefore subjected to a solderability test on a sampling basis before component insertion.

Recently the use of surface-mounted devices (SMD) has increased markedly in order to preclude parasitic inductance, and also to rationalize component insertion. It was possible to transfer the experience with SMD components obtained during the hybridization of film circuits to epoxy and Teflon substrates. This technology permits considerably closer spacing than is the case for wired components, and facilitates the use of computer controlled component inserting machines (**Fig. 6**). These machines operate with a low error rate and, moreover, offer the possibility of checking the identity of components before final assembly.

Following printed circuit assembly, the machine soldered modules are subjected to an in-circuit test. This shows up incorrect component insertions, damaged components and short or open circuits. In this way only substantially error-free modules are passed to the test departments. This is an essential prerequisite for the economic operation of the computer controlled automatic test equipment employed in the test departments.

Equipment assembly

Equipment assembly forms the last step in the process. The microwave modules and printed-circuit assemblies are mounted in a case (**Fig. 7**) and interconnected by means of suitable wiring. In contrast to other equipment used in telecommunication transmission, in which printed-circuit assemblies are inserted into racks or inset frames, higher demands are placed on the assembly of radio relay equipment, since microwave components with highly sensitive mechanical interfaces interoperate with printed-circuit assemblies. This also necessitates special steps in the test department, which are reported in [2].

Fig. 6 Automatic component insertion machine for surface-mounted devices (SMD)

Outlook

Even greater linking of successive steps in the production process stations will be a high priority aim for the production departments in the next several years.

For this purpose further work processes will have to be automated in order to further increase the quality, substantially shorten throughput times and to reduce stocks.

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Fig. 7 Large-scale assembly of equipment insets for the DRS 140/6700 radio relay system

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State of the Art and Future Trends in Digital Radio Relay Systems

The decision of most PTT administrations worldwide to digitize their telecommunication networks led in consequence to the introduction of completely new ranges of transmission equipment in the late seventies. In the field of radio relay engineering, this decision was followed by the development of a first generation of digital systems for the various network levels in the "classical" 1.7- to 11.2-GHz bands. These digital systems had to be largely compatible with the analog systems already in operation.

In this article, the authors first outline the position of radio relay transmission in telecommunication networks and generally compare the bandwidth efficiency of analog radio relay systems with that of digital systems. This is followed by a concise survey of the structure and features of the first generation systems, employing mainly QPSK (quaternary phase-shift keying) or 16-QAM (16-level quadrature amplitude modulation).

However, trends are already perceptibly heading in the direction of higher spectrum efficiency and even greater cost-effectiveness through the use of new kinds of digital systems employing multilevel modulation schemes and improved spectrum shaping and the application of adaptive diversity and equalization techniques. It also appears possible to implement cochannel operation with two orthogonally polarized bearers on one RF (frequency reuse) and thus achieve a considerable improvement in radio frequency (RF) band utilization. The methods and technologies associated with these second generation systems are discussed.

In addition to the classical frequency bands, the range above 11 GHz was opened up for digital systems at an early stage. It is only recently that an increased capacity requirement at regional and local network levels has emerged to stimulate similar adoption of spectrum efficient systems even at these network levels. This means that such areas will also require the use of new technologies and methods, which, in so far as they can already be defined, are briefly discussed.

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◁ Typical radio tower of the Deutsche Bundespost. DRS 140/... digital radio relay systems for the transmission of broadband digital signals in the long-haul network are mounted on an additional platform.

Radio relay systems in transmission networks

As long as the switching and transmission equipment used in telecommunication networks throughout the world was mainly analog, i.e. up to the end of the seventies, systems employing frequency modulation (FM) were virtually the standard in radio relay. The only exceptions were on very high-density routes with only a few drops and demanding an extremely high degree of spectrum efficiency. For links of this kind – e.g. from the Federal Republic of Germany to Berlin (West) [1] or on the high-density transcontinental routes in the USA [2] – SSB-AM (single-sideband amplitude modulation) was the preferred method of modulation. An important characteristic of the analog FM radio relay networks was that they enabled virtually identical systems to be used for telephone and TV signal transmission.

As digital switching equipment began to be used in telecommunication networks from the mid-seventies onwards, analog transmission ceased to be a cost-effective solution. This led to the development and introduction of a first generation of radio relay systems employing digital modulation schemes, QPSK and 16-QAM being preferred. Only in those exceptional cases where the required route transmission capacity could not be obtained with first generation digital radio relay systems, as on the above mentioned coast-to-coast links in the USA, did SSB-AM systems, now with transmultiplexers, continue to be used [2].

In the Deutsche Bundespost's radio relay network, digital radio relay systems for lower transmission capacities up to 34 Mbit/s were initially employed in the 1.9-, 13- and 15-GHz bands, followed in rapid succession by further systems for 140 Mbit/s at 3.9 and 11.2 GHz and, in exceptional cases, at 6.7 GHz. A 140-Mbit/s system at 13 GHz is also planned. Of considerable importance for the future is the decision that the existing digitized telecommunication network with the various services operating in separate networks – e.g. IDN – should evolve into the integrated services digital network ISDN.

This decision means that separate radio relay networks must be provided for telephone and TV signal transmission at

least for the time being. The TV network will continue to use existing analog modulation methods until suitable digital coding with an economical bit rate has been standardized for TV signals. Only then will it be possible to return to a common – by then digital – system for telephony and TV transmission [3].

The situation in transmission networks worldwide is being increasingly determined by the competition between radio relay and optical fiber transmission media. Whereas the transmission capacity of optical links can be increased almost indefinitely by increasing the fiber count, the transmission capacity on radio relay routes is essentially constrained by the available frequency band. Nevertheless, radio relay links offer distinct advantages, not only for inaccessible or undeveloped terrain but also for rapidly establishing a network which can be flexibly adapted to suit topographical and organizational constraints. Indeed, it is in conurbations, where right-of-way and infrastructural requirements often preclude line transmission systems, that radio relay links frequently appear to be the only feasible solution. Under these circumstances, the constantly increasing demand for transmission capacity in telecommunication networks is a particular challenge for radio relay. The future for radio relay in transmission networks is therefore definitely promising, provided two objectives can be attained. The first is to ensure cost-effectiveness compared with line transmission systems (this applies particularly to the cost of maintaining the required transmission quality on systems with high spectrum efficiency). The second is to provide the necessary transmission capacity through optimum utilization of the available frequency bands and by exploiting new frequency bands above 11 GHz.

In order to assess the present state of the art, the first part of this article will therefore compare the RF band utilization of analog radio relay systems with that of the first and second generation digital systems. The second part will provide a concise summary of the design features of the first generation digital radio relay systems currently in service. The characteristics of the emerging second generation systems will then be discussed, together with the techniques and technologies to be employed. The concluding section will describe the design, engineering and features of radio relay systems in the recently exploited frequency bands above 11 GHz.

RF band utilization of radio relay systems

Comparing the bandwidth of a 4-kHz analog telephone signal with the data rate of 64 kbit/s of a PCM telephone signal, we find that the transition from analog to digital telecommunication networks has not immediately improved the position of radio relay transmission in terms of frequency band utilization. Consequently, it must be a primary objective of digital radio relay engineering at least to match or if possible even exceed the spectrum efficiency of the previous analog systems. This can be achieved by consistently applying all the methods available – i.e. by using multilevel modulation schemes enabling the transmission rate to be reduced by means of serial-to-parallel bit conversion and by utilizing one RF channel frequency in two orthogonal polarizations (frequency reuse).

In any comparison of the spectrum efficiency of radio relay systems, a distinction must be drawn between spectrum efficiency per RF channel and RF band usage, i.e. the frequency band economy in the network as a whole. The spectrum efficiency per channel only takes into account the number of voice channels which can be transmitted per RF carrier, referred to the transmission bandwidth of the channel. It takes no account of the given RF channel arrangement. The RF band usage, however, is a measure of the transmission capacity of the particular RF band, referred to the width of that band, in a radio relay network. This means that, in addition to the important criteria for spectrum efficiency per RF carrrier (e.g. the modulation method), a number of other factors must be taken into account. These include shaping or filtering of the modulated spectrum, characteristics of channel branching filters, polarization diplexers and antennas, the linearity of the signal paths in the transmitter and receiver, the adaptive equalizer and combiner techniques used, and the effect of any error correction coding employed. The interplay between all these factors must be controlled so as to maximize RF band usage for a given radio relay band with its standardized RF channel arrangement, even under critical propagation conditions. This requires adequate *C/I* and *C/N* ratios and low distortion to be maintained during transmission in compliance with CCIR bit error ratio (*BER*) recommendations relating to quality and availability [4].

In order to provide a basis for discussing the present state of RF band usage in radio relay systems, the **Table** compares the relevant band usage data for analog and digital systems. For the digital systems, a distinction is drawn between the state of development achieved by the first generation systems and what appears to be a realistic projection for the second generation systems. The 6.2-GHz band, a typical long-haul frequency range, was selected for the comparison in order to cover both frequency-modulated systems with overlapping sidebands [5] and systems using SSB-AM [2, 6]. As the 6.2-GHz band was employed for digital transmission for the first time in the USA, the systems quoted in the literature almost invariably use the American hierarchy given in the **Table**. Since these systems are assumed to be used in telecommunication networks for the purpose of telephony, the frequency band capacity and RF band usage given in the **Table** are calculated on the basis of two-way traffic (voice circuits).

Analog radio relay systems

For analog modulation methods, it is immediately clear from the **Table** that the RF band usage of the FM 1800/6200 system [7] used in long-haul networks worldwide is approximately 30 voice circuits per MHz. The corresponding value of 31.5 voice circuits per MHz for FM 2700/6700 long-haul systems in the 6.7-GHz band is roughly comparable. By increasing the cross-polarization discrimination to over 38 dB and reducing the frequency deviation, it has been possible to reduce adjacent channel interference sufficiently to enable an FM 2700/6200 system to be realized [5]. This system, which employs overlapping sidebands and was developed in Japan, has enabled the RF band usage of FM systems to be increased to 43 voice circuits per MHz. However, it may be assumed that the outage prob-

ability of this system in the presence of dispersive fading is less favorable than with FM 1800/6200. The broadband systems employing SSB-AM originally designed by Bell Laboratories (system AR6A) were developed specially for the transcontinental routes in the USA and provide up to 42,000 voice circuits with an RF band usage of up to 84 voice circuits per MHz in the 6.2-GHz band [2, 6]. These systems impose extremely stringent requirements on the linearity of all the components in the signal path. In order to achieve the desired availability, they employ dynamic amplitude equalizers and highly specialized protection switching systems. The above mentioned systems are, as a result, extremely complex, yet they provide the reference standard for frequency band utilization on digital radio relay systems.

First generation digital radio relay systems

First generation digital radio relay systems employing mainly QPSK and 16-QAM do not compare with analog systems in terms of RF band usage and not even with FM analog systems. The RF band usage, for instance, of a 16-QAM system operating at 90 Mbit/s (2 × DS3) is approximately 21 voice circuits per MHz (as compared with 22.5 voice circuits per MHz for DRS 140/6700), which is only about ⅔ of that achieved on FM 1800/6200 [8]; QPSK systems are even worse in this respect [9]. However, by using 64-QAM modulation, it has recently been possible for the first time to develop digital systems with an RF band usage of 32 voice circuits per MHz, which is even slightly superior to that of FM 1800/6200 [10]. The required adjacent channel isolation has been mainly achieved by progressive spectrum shaping (roll-off factor 0.25), so that no particularly stringent requirements have to be placed on cross-polarization discrimination. The basic design of this 64-QAM system is, therefore, not markedly different from that of familiar 16-QAM systems.

However, a much greater advance in RF band usage is made possible by the introduction of cochannel operation on a cross-polarized basis using both polarizations (frequency reuse). Initial experiments with 140-Mbit/s 16-QAM systems operating in the 6.7-GHz band with a roll-off factor of 0.2 indicate that it is possible to achieve an RF band usage of over 40 voice circuits per MHz, i.e. about 50% of the band usage of SSB-AM systems [11]. However, as the required cross-polarization discrimination of some 28 dB has to be markedly higher than for normal operation without frequency reuse, it remains to be seen whether it will be possible to achieve the CCIR quality objectives without adaptive cross-polarization interference cancellers (XPIC). The purpose of an XPIC is similar to that of an adaptive baseband equalizer regarding the crosstalk between the I and Q channels, namely to provide adequate suppression of the crosstalk between the modulated RF carriers of a vertically and horizontally polarized radio frequency in the event of depolarization. The adaptive signal processing required for this purpose between systems or system sections in order to optimize transmission is, however, itself one of the most important features of second generation digital radio relay systems, so that the incorporation of an XPIC would result in such a system being classified as second generation.

Second generation digital radio relay systems

As indicated above, second generation digital radio relay systems are characterized by the fact that signal processing – mainly of an adaptive nature – takes

Modulation scheme		Bit rate per RF carrier (Mbit/s)	Voice channels per RF carrier	RF channel arrangement	Spectrum efficiency $\left(\frac{\text{bit/s}}{\text{Hz}}\right)$	RF band capacity (voice circuits)	RF band usage (voice circuits per MHz)
Analog modulation schemes							
FM Non-overlapping sidebands	[6]	–	1800	Interleaved	–	14400	29
FM Overlapping sidebands	[7]	–	2700	Interleaved	–	21600	43
	[2]	–	6000		–	42000	84
SSB*-AM	[8]	–	5400		–	37800	76
Digital modulation schemes First generation systems							
QPSK	[9]	45	672	Interleaved	1.7	5376	11
QPSK	[9]	45	672	Cochannel	3.4	10752	21.5
16-QAM	[10]	90	1344	Interleaved	3.4	10752	21.5
16-QAM	comparable [12]	90	1344	Cochannel	6.8	21504	43
64-QAM	[11]	135	2016	Interleaved	4.7	16128	32
Digital modulation schemes Second generation systems							
64-QAM hypothetical		135	2016	Cochannel	9.4	32256	64.5
256 QAM	[13]	180	2688	Interleaved	6.8	21504	43
256-QAM hypothetical		180	2688	Cochannel	13.6	43008	86

* Single sideband

Table RF band utilization for various modulation schemes using the 6.2-GHz band as an example

RF band: 5925 to 6425 MHz; Channel spacing: 29.65 MHz; RF channel pairs: 8; RF bandwidth: 500 MHz;

place between systems or at least system sections in order to optimize transmission. These systems therefore have a specifically higher "intelligence level" than those of the first generation. It can already be recognized that these systems with their greater "intelligence" will achieve the CCIR quality and availability objectives even when higher-order modulation schemes are employed – i.e. 256 QAM.

The **Table** lists three system configurations likely to be realized in the next few years. As a first step, 256-QAM systems for interleaved patterns will probably be realized with utilization of the RF channels on a single polarization; suitable experimental 256-QAM modems for a bit rate of 120 Mbit/s have already been reported [12]. The RF band usage of such systems (43 voice circuits per MHz) is on a par with that of 16-QAM systems employing cochannel operation and frequency reuse.

The next step towards higher spectrum efficiency is likely to be the implementation of cochannel operation using both polarizations in 64-QAM systems. Here the RF band usage (64.5 voice circuits per MHz) is almost 80% of that on SSB-AM systems. The latest development in prospect for the time being – and it is still of a hypothetical nature – involves 256-QAM systems employing frequency reuse. With systems of this kind, it may be possible to achieve 86 voice circuits per MHz, slightly exceeding the RF band usage even of SSB-AM systems.

Turning to the situation in present-day radio relay networks, we find that the systems employed are mainly analog and first generation digital. In the "classical" frequency bands up to 11 GHz, the RF band usage is therefore unlikely to exceed on average 20 to 25 voice circuits per MHz, taking into account the considerable proportion of operational narrowband and mediumband systems with their lower spectrum efficiency. As radio relay networks are converted in future to second generation systems, the above spectrum efficiency comparison suggests that it will be possible to increase available transmission capacity considerably, by a factor of two or three. When the frequency bands above 11 GHz are also taken into account, there is no forseeable shortage of available transmission capacity for radio relay, at least in the medium term. And this still takes no account of the scope for increasing capacity by, in particular, signal transmission with different source encoding – e.g. ADPCM (adaptive differential PCM) – and with DSI (digital speech interpolation) or a combination of the two, DSI-ADPCM [13].

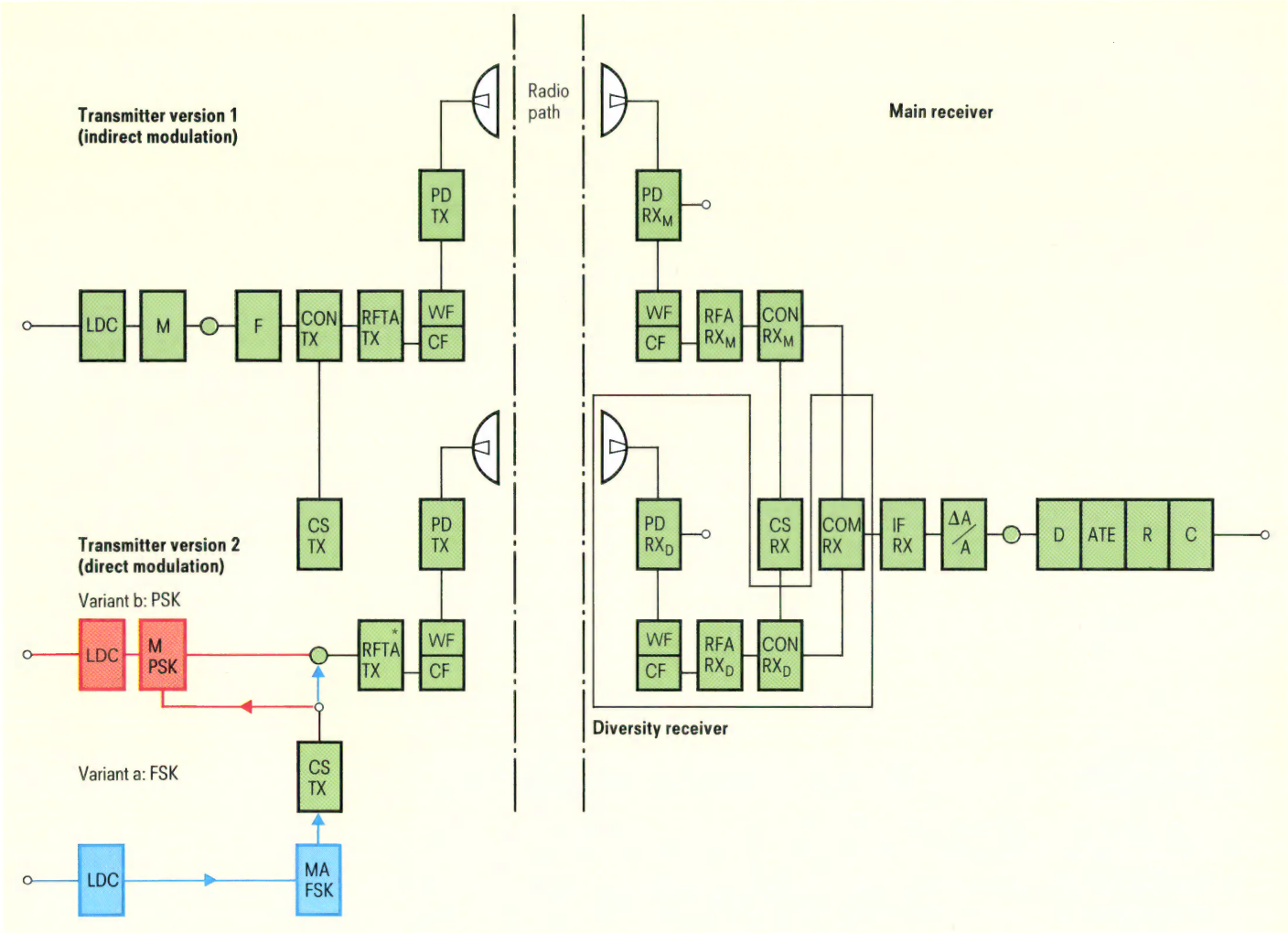
Design and features of first generation digital radio relay systems in the classical frequency bands

The basic design of first generation digital radio relay systems, as shown in **Fig. 1**, does not differ fundamentally from that of the analog FM radio relay systems employed to date. This applies particularly to the microwave and intermediate-frequency sections of systems. This meant that, as long as no multilevel modulation schemes (e.g. 16-QAM) were used, it was possible for the IF interfaces of the existing long-haul analog radio relay systems (version 1) to be connected to QPSK or 8PSK digital modems without substantial modification to the radio units for digital transmission [14]. It was possible to adopt the same approach on narrow- and mediumband analog systems employing direct modulation of the RF carrier in short-haul networks. On the transmit side of these systems, there were two variants of this approach. In the first variant, the microwave oscillator was employed as an RF modulator with digital instead of analog frequency modulation, i.e. FSK, the only significant modification required being to the baseband section of the modulator [14]. In the second variant, the carrier generated in the microwave oscillator was phase-shift-keyed in a following RF modulator (second variant) [14]. The linearity of the existing analog IF (intermediate-frequency) and RF modules was usually just about adequate for implementing digital systems particularly when using OQPSK (offset QPSK) and FSK. Virtually the same applies to the receive side of these systems – with the exception of the adaptive frequency-domain equalizers required in the IF sections. Consequently, in the transition from analog to digital systems there was no need initially to introduce new technologies apart from the digital circuitry in the modem modules.

The situation changed substantially with the introduction of 16- or 64-QAM broadband systems for 140 Mbit/s. These modulation schemes are much more sensitive than 8PSK or even QPSK to nonlinearities, particularly amplitude distortions and amplitude-to-phase conversions, in the transmitter and receiver signal paths [15]. It was therefore necessary to linearize significantly the response of the components in the IF section and that of the RF components – mainly the converters and amplifiers [14]. The RF transmit amplifiers in particular may be major contributors to nonlinear distortions in the signal path. Whereas amplifiers with nominal output powers of up to 1 W can be suitably linearized using back-off, at higher transmitted power levels it is necessary to provide predistortion in order to linearize the system as a whole. The reason for this is that the magnitude of the power then required by the amplifier for back-off implementation becomes unacceptable in terms of the reliability of the system. In response to these requirements, the amplifier technologies used were also changed. Whereas FM systems could generally operate with nonlinear or even limiting transmit amplifiers (e.g. injection-locked Impatt oscillators or class C amplifiers incorporating bipolar transistors [14], 16-QAM systems require linear amplifiers equipped either with power GaAs FETs or highly linear traveling-wave tubes.

With multilevel modulation schemes being more sensitive to dispersive fading, protection of the transmission link by space diversity with combiner reception is required in a larger number of applications – this applies particularly to critical radio paths prone to deep fades [15]. Even with an adequate receive level, the resultant amplitude and phase distortions may be so severe – especially in the nonminimum phase case – as to require the use of adaptive time-domain equalizers in the baseband in addition to the above adaptive frequency-domain amplitude equalizers in the IF section. Transversal equalizers have proved a particularly effective solution, due to their high performance and stability allied to their rapid response [11, 14].

Many of the signal processing operations taking place at high speed in systems of this kind require an extremely large number of transistor functions. This led very rapidly to large-scale integration of



* Optional

Δ A/A	Adaptive IF frequency domain equalizer	IF	Intermediate frequency	RFA	Radio frequency (RF) amplifier
ATE	Adaptive time-domain equalizer	LDC	Line decoder	RFTA	RF transmitting amplifier
C	Line coder	M	Modulator	RX	Receiver
CF	Channel branching filter	MA	Modulation amplifier	RX_D	Diversity receiver
COM	Combiner	PD	Polarization diplexer	RX_M	Main receiver
CON	Converter	PSK	Phase-shift keying	TX	Transmitter
CS	Carrier supply	R	Regenerator	WF	Waveguide feeder
FSK	Frequency-shift keying				

Fig. 1 Basic design of first generation digital radio relay systems

entire circuit complexes into ECL (emitter-coupled logic) gate arrays. It is now possible to realize arrays with up to 2500 gates and delay times of ≤ 0.35 ms [15]. Thus, it is only since the introduction of multilevel modulation schemes, i.e. 16-QAM and 64-QAM systems, that the transition from analog to digital radio relay has stimulated technological advances in many areas. This applies particularly to the area of microwave components such as oscillators, converters, circulators, filters and amplifiers. Requirements imposed by these systems have led to new testing methods and development processes enabling phase and amplitude instabilities or hits, which are a direct source of bit error bursts, to be virtually eliminated.

Design and features of second generation digital radio relay systems

As stated at the outset, second generation radio relay systems aim at considerably better RF band usage compared with the previous broadband systems (**Table**). This can be achieved by employing modulation schemes with an even higher number of levels, such as 64- and 256-QAM, combined with cochannel operation using both polarizations. The technical demands on such systems are in many ways much more stringent than for the first generation systems. The linearity of the signal paths in transmitter and receiver must be almost the same as that of SSB-AM systems; in addition, the signal-to-noise ratio and the phase and amplitude stability (freedom from hits) of all the carriers must meet extremely strict requirements. A particularly important factor, however, is the high sensitivity to anomalies in propagation. In addition to the minimum and nonminimum phase distortions caused by dispersive fading, there is another particularly troublesome source of interference in cochannel operation resulting from the propagation-induced reduction in cross-polarization discrimination (depolarization).

In order to solve these problems, it will be necessary to incorporate a number of additional measures when developing second generation systems. **Fig. 2** shows some of these in a functional diagram for a two-system configuration employing cochannel operation on two polarizations. Adaptive, i.e. self-adjusting, techniques are likely to be employed to a much greater extent than up to now. An important aspect is that these techniques will no longer be applied solely to self-contained modules, as was previously the case for amplitude or time-domain equalizers; instead, adaptive signal processing will now occur between system sections and – as shown in **Fig. 2** – between systems in order to optimize the transmission characteristics:

- In order to increase the *linearity*, particularly on the transmit side, fixed predistortion is unlikely to be an adequate solution in all cases. Since small time-related variations in the transmission characteristics of the modules already cause a noticeable degradation, it will be necessary to consider adaptive predistortion for linearizing the entire signal path in the transmitter.

- In order to ensure that the required *signal-to-noise ratio (S/N)* is achieved, the noise contributions of the modules in the signal path and especially the receive noise figures will have to be reduced still further. At the same time, it will be necessary for the RF amplifiers to be operated nearer to their overload limit than previously in order to increase the transmitted power. The adaptive predistortion mentioned above appears to allow this. As these measures are not likely to be adequate in all cases, increasing use will probably be made of FEC (forward error correction), thereby decreasing the required signal-to-noise ratio by some 2 to 3 dB. Another very important factor will be the reduction of the insertion loss of the antenna feeders. This can be achieved, for instance, by using overmoded waveguides [14].

The *immunity of the systems to dispersive fading* will assume increasing importance. In order to make the systems sufficiently immune to these effects, further measures will be required in addition to the adaptive amplitude and time-domain equalizers employed to date. Apart from the enhanced performance likely to be obtained from the time-domain equalizers by all-digital designs, it will also be necessary to improve the combiner algorithm for space diversity, the aim being not so much to maximize the receive level (in-phase or maximum power combiner), but to minimize distortion. Consequently, combiner control – as illustrated in **Fig. 2** – will have to be decision-oriented. It remains unresolved whether the signals should be combined at RF, IF or at baseband.

- An additional source of interference affecting systems operating on a cochannel basis (frequency reuse) is depolarization due to rain or multipath propagation, resulting in crosstalk between the orthogonally polarized RF signals. In order to protect systems against this effect, it will be necessary to use the adaptive cross-polarization interference cancelers (XPICs) mentioned earlier. System performance with respect both to dispersive fading and depolarization is likely to be improved still further by adaptive antennas [14], whereby both the polarization plane and – within narrow limits – the electrical boresight of the antenna are controlled on a decision-oriented basis.

In adopting all these measures for optimizing the transmission characteristics of second generation digital radio relay systems, considerable additional expenditure will be required for integrated circuits and tuning procedures. The need to be cost-effective relative to line transmission systems, mentioned at the outset, means that it is imperative to find ways of reducing manufacturing costs. This cost reduction, as far as one can tell, will only be achieved through technological breakthroughs in key areas of semiconductors, circuit and fabrication technology and through advances in test and adjustment techniques. However, perceptible progress is being made in these areas, especially in semiconductor technology with large-scale silicon integrated circuits and monolithic microwave integrated circuits based on GaAs, and also in the production process with the introduction of SMDs (surface-mounted devices). These developments enable automatic component insertion, the use of computer numerically controlled (CNC) machining centers for microwave component fabrication and of automatic radio relay test and measuring sets with bus control [14], all of which suggests that this goal is achievable.

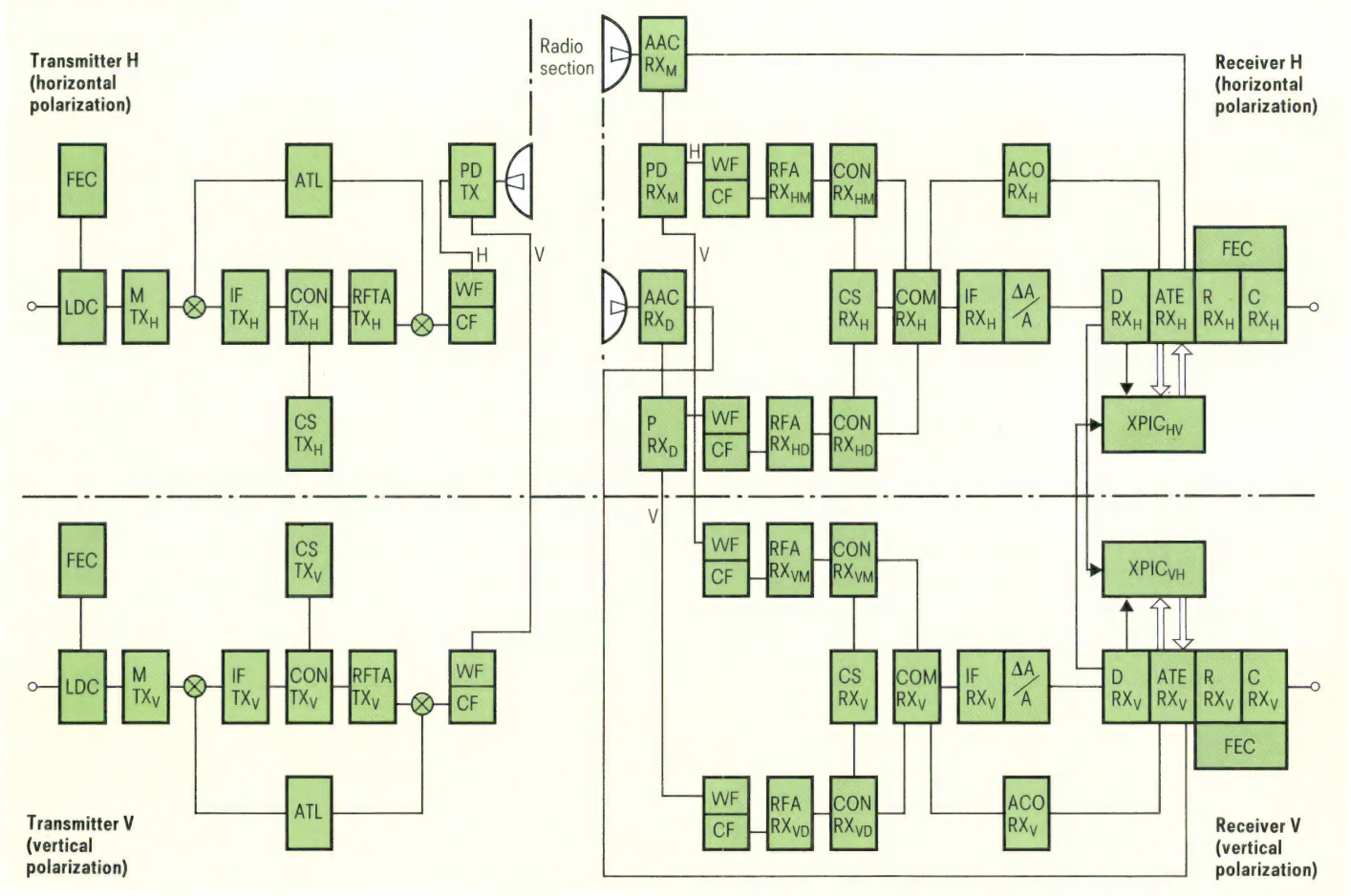
The crucial factor will, however, be in concentrating increasingly complex signal-processing functions in large-scale integrated circuits. Until now this requirement has been met by semi-custom gate arrays in ECL technology available as LSI devices with a medium level of integration (2500 gate functions) [14]. In the future, however, ACMOS technology (advanced CMOS) will make it possible to produce custom VLSI devices with high processing speeds and an increased level of integration (approximately 10,000 gate functions) for radio relay applications. This will provide an immediate economy in allowing further concentration of existing integrated circuit functions; in addition, it will allow the analog-to-digital conversion within the system to be relocated, thereby enabling a number of other circuit functions to be digitized and hence integrated. This could allow many of the previously mentioned adaptive functions for optimizing transmission to be incorporated in the VLSI circuits, thus reducing their significance as a cost factor.

Features, potential applications, design and engineering of digital radio relay systems above 11 GHz

Features

With the increased attenuation due to rain, the hop lengths achievable in the frequency range above 11 GHz are significantly shorter than the hop length of approximately 50 km normally used in existing long-haul networks. For central European climatic conditions and an annual unavailability of 0.01%, typical hop lengths are around 25 km at 13 GHz, approximately 10 km at 20 GHz and only about 5 km at 30 GHz. This means that a larger number of relay stations must be provided to span a particular distance than in lower frequency bands. For this reason we will find a suitable infrastructure certainly in conurbations but not on long-haul routes when adopting frequency bands above 15 GHz.

As a consequence, digital radio relay systems above 11 GHz can only be used



ΔA/A	Adaptive IF frequency domain equalizer	IF	Intermediate Frequency	RX_{HM}	Main receiver (horizontally polarized)
AAC	Adaptive antenna diagram control	H	Horizontal polarization	RX_M	Main receiver (both polarizations)
ACO	Adaptive combiner optimization	LDC	Line decoder	RX_V	Receiver (vertically polarized)
ATE	Adaptive time-domain equalizer	M	Modulator	RX_{VD}	Diversity receiver (vertically polarized)
ATL	Adaptive transmitter linearization	PD	Polarization diplexer	RX_{VM}	Main receiver (vertically polarized)
C	Line coder	R	Regenerator	TX	Transmitter (both polarizations)
CF	Channel branching filter	RFA	Radio frequency (RF) amplifier (LNA)	TX_H	Transmitter (horizontally polarized)
COM	Combiner	RFTA	RF transmitting amplifier	TX_V	Transmitter (vertically polarized)
CON	Converter	RX_D	Diversity receiver (both polarizations)	V	Vertical polarization
CS	Carrier supply	RX_H	Receiver (horizontally polarized)	WF	Waveguide feeder
D	Demodulator	RX_{HD}	Diversity receiver (horizontally polarized)	XPIC	Cross-polarization interference canceler
FEC	Forward error correction				

Fig. 2 Basic design of second generation digital radio relay systems

cost-effectively where the distance to be spanned is reasonable in relation to the achievable hop length, i.e. in regional and, more especially, local networks. The Deutsche Bundespost's planning, e.g. for the 18-GHz band, provides for up to 3 hops to be cascaded [3].

As there was initially no demand for local and regional networks of this kind, the frequency bands above 11 GHz were not exploited to any great extent until the mid-seventies. The systems developed at that time employ mainly QPSK and fall into two equipment categories. The first category contains broadband systems transmitting 400 Mbit/s or 274 Mbit/s and designed for installation in heatable shelters near the antenna. The other category comprises narrowband systems in weatherproof housings with integral antenna and capable of operation over the entire ambient temperature range without additional heating [16]. The RF band usage of these systems was still relatively low, with no more than 10 to 15 voice circuits per MHz. This was because the wide and unexploited frequency bands permitted the use of robust but spectrally inefficient modulation schemes.

Applications

Nowadays there is an increasing demand for transmission capacity for all bit rates from 2 to over 140 Mbit/s in the 13-, 15-, 18.7- and 23-GHz bands both in regional networks and, more particularly, in local networks.

In addition, a number of administrations intend to use these frequency bands to connect telecommunication centers in conurbations to long-haul routes (route extension spurs) in order to facilitate frequency coordination; it is also planned to connect remote radio transmission stations for economical, single-medium routing. For these reasons, the Deutsche Bundespost is already considering additionally utilizing the 28-GHz band for 34-Mbit/s and 140-Mbit/s systems [4]. Furthermore, the Deutsche

Bundespost sees possible applications for digital point-to-multipoint systems with TDMA (time-division multiple access) in the 23-GHz band.

Design

With this diversified development in capacity demand, the trend is for the frequency bands above 11 GHz to be used by two large system groups of different design:

- *Low-cost narrowband outdoor systems in weatherproof housings which can be mounted on poles or buildings;* preferred modulation schemes include FSK and QPSK, with the modems generally incorporated in the radio units [14].

- *Broadband systems with improved spectrum efficiency for transmitting ≥ 140 Mbit/s per radio frequency;* possible modulation schemes are 16-QAM and in some cases 64-QAM, if the transmission bands are to be put to reasonably efficient use. For example, in the 18-GHz band, 560 Mbit/s per radio frequency could be transmitted with 110-MHz, or even 80-MHz, channel spacing using a 16-QAM system with cochannel operation and frequency reuse to provide an RF band usage of 31 or 43 voice circuits, respectively, per MHz [14].

Since the modem equipment required for this purpose is preferably operated in a controlled environment and the waveguide runs used for the antenna feeder introduce excessive loss in the fundamental mode at these high frequencies, there are three possible approaches to designing these units:

- The modem equipment is installed in heatable shelters near the antenna, with all the units in a controlled environment.

- Modems are accommodated in station buildings and for radio units in shelters near the antenna or in weatherproof housings.

- The third solution makes use of overmoded waveguides for the antenna feeders, so that the attenuation can be reduced to approximately one third of the decibel value of waveguides operated in the fundamental mode [14]. This enables the equipment to be accommodated in the usual way in station buildings, with the well-established advantages in terms of accessibility and maintainability.

Engineering

As stated earlier, digital radio relay systems above 11 GHz employ shorter hop lengths due to rain attenuation. Consequently, their use is limited to the lower network hierarchy level and particularly to conurbations. This will remain the case as long as technical advances in the radio relay field – e.g. in signal processing (see section on second generation radio relay equipment) – have an across-the-board effect on systems, i.e. irrespective of the frequency band. However, GaAs-based monolithic microwave integrated circuits (MMICs) could change this situation. By integrating a large number of discrete microwave and IF functions of a radio relay system on a single GaAs chip, they could conceivably provide extremely economical implementations of entire system sections. In this respect, high-frequency systems will benefit particularly, as the low reactances required are capable of realization on the chip. Although MMIC technology for low and medium volume production is not yet economically viable, it is likely that design and production conditions comparable to those of semicustom LSI circuits [14] could be created, thereby providing a significant improvement in cost-effectiveness particularly for radio relay systems above 11 GHz.

Summary

The importance of radio relay as a transmission medium will continue to progress provided two main objectives are achieved: one is to ensure the cost-effectiveness of this medium, the other to provide the required transmission capacity. The latter objective can be achieved now and in the future by developing a second generation of digital radio relay systems employing multilevel modulation schemes and adaptive algorithms for optimizing transmission, and also by exploiting more of the frequency spectrum above 11 GHz. The consistent application of advances in custom VLSI devices, MMICs, surface acoustic wave (SAW) and ceramic-based resonator and filter technology as well as microwave GaAs semiconductor technology will make it possible even to extend the scope of the radio relay medium as an economical alternative to other media.

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Wolfgang Noack and Hans-Jörg Thaler

Planning Considerations for High-Capacity Digital Radio Relay Systems

Signal transmission in modern telecommunication networks is based on two different transmission technologies. Cable systems rely on a fixed physical link between the nodes to be connected, which is realized either as a metallic or a fiber-optic cable. In this case, the transmission channel is spatially well-defined, isolated and practically time-invariant. Alternatively, radio systems can provide a means of transmission between points without an artifical and expensive medium – either as satellite links, terrestrial line-of-sight links or even as mobile radio systems for connections to mobile stations. The main characteristics distinguishing the atmosphere from its counterpart as a transmission medium are the result of its open structure and the time-variant nature of the propagation characteristics. The former gives rise to interference among different links, while the latter leads to fading and propagation distortion. Both effects have led to the introduction of adaptive signal processing techniques to guarantee the required transmission quality.

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To achieve a technically and economically optimized transmission solution, radio systems require complex planning at several interactive levels. Such planning considerations must start at the equipment design level and take into account the nature of the propagation channel; they finally culminate in guidelines for radio path and radio network design.

The aim of these planning efforts is the realization of technically and economically optimized solutions for radio transmission systems based on agreed performance and availability standards, such as those specified in CCITT and CCIR recommendations.

Today, the need to better utilize the limited available bandwidth is the driving force behind progress in radio transmission techniques. Bandwidth efficiency can be improved by the application of higher-level modulation schemes, such as quadrature amplitude modulation (QAM) with 4, 16, 64 or even 256 states. In addition, it can be approximately doubled by simultaneous transmission on two orthogonal polarizations. Both approaches are not only increasingly demanding in terms of equipment design and implementation, but also with respect to planning at all levels. They must take into account the increasing sensitivity to imperfections and interference. Therefore, interference considerations become increasingly important for multilevel modulation schemes and are a dominant factor in equipment design and the final design of the radio path and network.

Interference, therefore, occupies a central position in this contribution on planning considerations for high-capacity digital radio systems. The authors open with an introduction into radio system fundamentals and a review of performance and availability objectives as delineated in CCITT and CCIR recommendations. This is followed by a discussion of the main effects and mechanisms that degrade performance and availability of radio links. The behavior of radio propagation channels is then described, and standard prediction formulas for multipath fading and rain attenuation are presented.

In the following main section all significant contributions to system impairments by noise and interference are discussed in detail, using average fading depth values for the channel bandwidth occupied. These considerations lead to guidelines for the required isolation and discrimination values against interference. A review of dispersive fading effects and current techniques to include them in outage predictions of will be given in a future article.

Principles of multilevel modulation methods

Error-free transmission of a binary digital signal at a symbol rate of $f_s = 1/T$ even with (theoretically) infinite spectrum bandwidth requires an ideal (not realizable) low-pass channel, whose cutoff frequency is given by the Nyquist frequency of $f_N = f_s/2$. This extremely bandwidth-efficient channel can in practice be approximated by smooth low-pass filter characteristics which, subject to certain conditions, also produce pulse responses without intersymbol interference. A Nyquist channel of this type usually has a cosine roll-off characteristic. Its transfer function, $H(f)$, is described in the transition region by a cosine function.

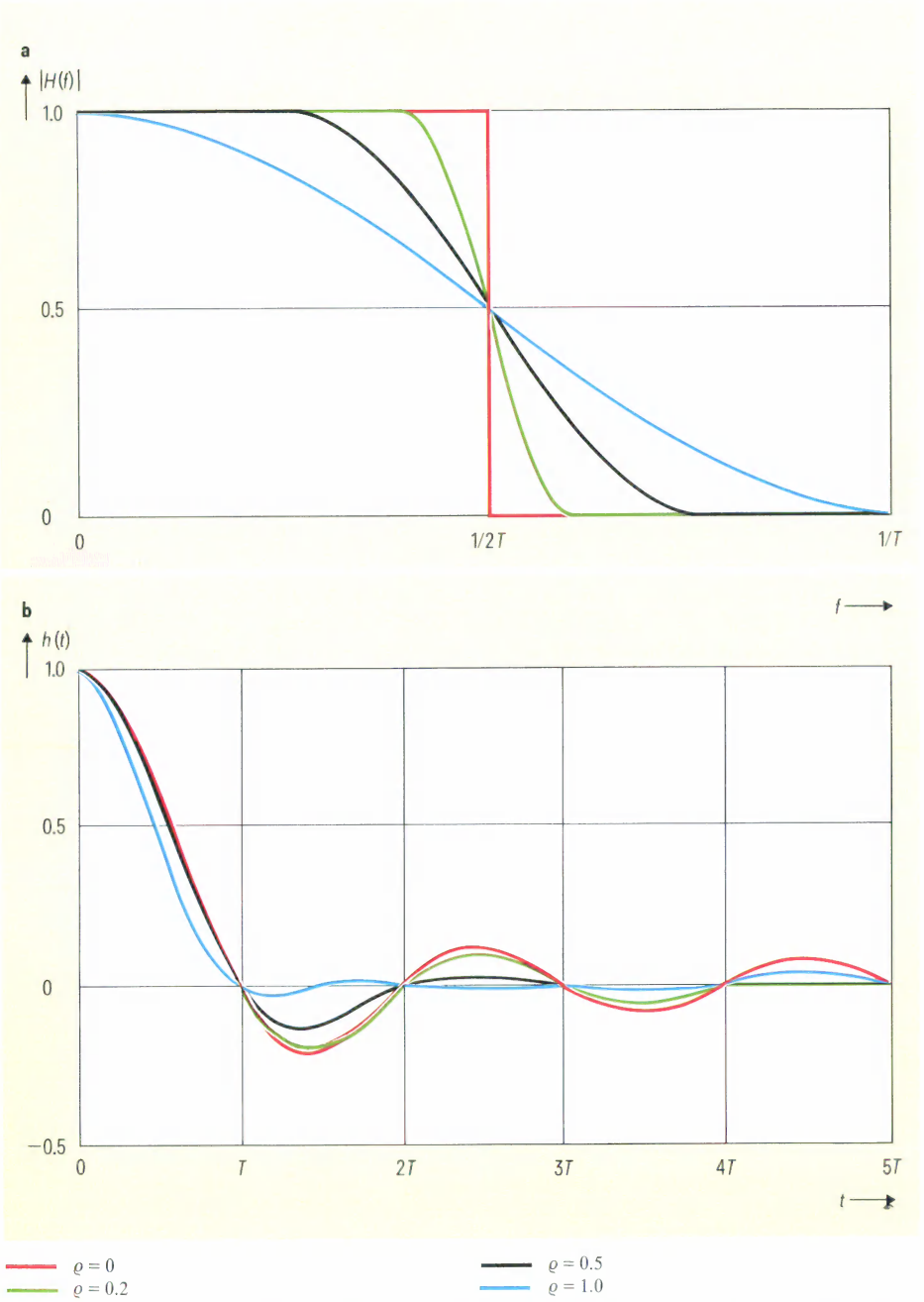


Fig. 1 Characteristics of a cosine roll-off channel at different roll-off factors: transmission function $|H(f)|$ in the frequency band (b); pulse response $|h(t)|$ in time (b)

$$H(f) = 1, \text{ if } |f| \leq f_N(1-\varrho);$$

$$H(f) = \frac{1}{2}\left[1 + \cos\left(\frac{\pi}{2} \cdot \frac{f - f_N}{\varrho \cdot f_N} + \frac{\pi}{2}\right)\right],$$

$$\text{if } f_N(1-\varrho) \leq |f| \leq f_N(1+\varrho);$$

$$H(f) = 0, \text{ if } |f| \geq f_N(1+\varrho).$$

The roll-off factor (ϱ) indicates the additional bandwidth required (above the Nyquist frequency) (**Fig. 1**).

The conditions prevailing in the low-pass channel are applicable to the band-pass channel when modulated. With linear modulation, two identical sidebands are obtained. They are replicas of the modulating signal spectrum and together occupy double the bandwidth of the baseband channel. In order to arrive at the same bandwidth utilization (bit rate per bandwidth) as the low-pass channel, it is necessary either to suppress a sideband (single-sideband modulation) or to utilize the bandwidth a second time by similar modulation of an orthogonal quadrature carrier. With quadrature amplitude modulation (QAM), which involves two carrier signals phase-shifted by 90° being modulated by two binary signals at half the signaling rate, the same spectrum utilization is then obtained as in the comparable low-pass channel with binary transmission.

As on all digital transmission systems it is possible to improve the spectrum utilization by a factor of N relative to binary transmission by combining N bits to form $n = 2^N$ symbols. With binary modulation of two quadrature carriers there are $2 \times 2 = 4$ states for the resulting carrier vector; this is termed 4 QAM. With four-level (quaternary) modulation there are $4 \times 4 = 16$ possible states (16 QAM). The other versions of higher-level QAM are listed in **Table 1**.

For a given mean power of the QAM signal the separation between adjacent signal states decreases at approximately $1/\sqrt{n} = 2^{N/2}$. In addition, if the number of levels is increased for a given mean power, the associated peak power rises. The interference in the transmission channel that the receiver can tolerate while still satisfactorily detecting a transmitted symbol also decreases. It is for this reason that the signal-to-noise ratio (S/N) requirement for a fixed error probability rises as the number of states increases. The requirement is about 6 dB higher every time the number of states ($\sqrt{n}$) per quadrature carrier is doubled. Generally, the improved spectrum utilization of higher-level modulation methods is associated with a greater sensitivity to noise and interference, which must be compensated by an increased S/N requirement. **Table 1** also contains S/N values in dB for four different bit error ratios (BER).

Besides the increasing S/N, multilevel modulation schemes are characterized by a higher vulnerability to linear and nonlinear distortion in the transmission path. Multipath propagation in the propagation medium itself causes unavoidable linear distortion. It is obvious from time-domain considerations of a two-path propagation model that the tolerable unwanted propagated signal (delayed echo) decreases with an increasing number of modulation levels and also with a decreasing roll-off factor. This results from the longer time spread and the higher amplitudes of channel pulse responses with the decreasing roll-off factor, as shown in **Fig. 1**.

Modulation method	4 QAM	16 QAM	64 QAM	256 QAM
Bits per symbol (N)	2	4	6	8
Spectrum utilization (bit/s/Hz)				
for $\varrho = 0$*	2	4	6	8
for $\varrho = 0.5$*	1.33	2.67	4.00	5.33
for $\varrho = 0.5$**	2.5	3.5	5.0	7.0
Signal-to-noise ratio (dB) (theoretical, diff. coded)				
for $BER = 10^{-3}$	10.3	17.0	22.9	28.6
for $BER = 10^{-6}$	13.8	20.6	26.7	32.6
for $BER = 10^{-9}$	15.7	22.6	28.7	34.7
for $BER = 10^{-12}$	16.9	23.3	30.1	36.1

* One polarization only (ideal)
** Both polarizations (real)

Table 1 Spectrum utilization and signal-to-noise ratio requirement on systems employing quadrature amplitude modulation (QAM)

The spectral shaping according to the Nyquist criterion is usually performed at IF or at baseband by specially designed Nyquist or roll-off filters. An attractive solution is provided by the application of high-precision surface acoustic wave (SAW) IF filters which give almost ideal Nyquist channel response and also very good filter discrimination against interfering adjacent channel signals.

Performance and availability objectives

Performance and availability objectives for digital reference paths with digital radio relay systems as transmission medium are recommended by CCIR in accordance with the basic recommendations of CCITT. Up to now values for the different performance parameters have been specified only for the high-grade portion of the reference link. They refer to the bit error performance of 64-kbit/s channels; the transformation of the given objectives to the basic channel bit rate is still under study. **Table 2** gives an overview of the performance criteria and the allocated time percentages for the different network levels (values in brackets are preliminary examples, proposed by one administration [1]).

The recommended performance objectives for a real radio link with a length (L) between 280 km and 2500 km and forming part of a high-grade circuit are specified in CCIR Rec. 634. The three criteria, *severely errored seconds* (SES, $BER = 10^{-3}$), *degraded minutes* (DM, $BER = 10^{-6}$) and *errored seconds* (ES, seconds with at least one error), are allocated on a linear scale of time percentages with length.

SES: $BER \geq 10^{-3}$ in $\frac{L}{2500} \cdot 0.054\%$ of the time of any month

DM: $BER \geq 10^{-6}$ in $\frac{L}{2500} \cdot 0.4\%$ of the time of any month

ES: in $\frac{L}{2500} \cdot 0.32\%$ of the time of any month.

The *residual bit error ratio* (RBER) criterion is scaled down directly with length.

RBER: $BER \leq \frac{L}{2500} \cdot 5 \cdot 10^{-9}$ in 50% of the time of any month.

Performance objectives for links shorter than 280 km are still being studied. The planning of individual hops with a length (d) is usually based on the following assumptions for the two marginal parameters:

$L \geq 280$ km

SES: $BER \geq 10^{-3}$ in $\frac{d}{2500} \cdot 0.054\%$ of the time of any month

RBER: $BER \leq \frac{d}{2500} \cdot 5 \cdot 10^{-9}$ in 50% of the time of any month.

$L < 280$ km

SES: $BER \geq 10^{-3}$ in $\frac{280}{L} \cdot \frac{d}{2500} \cdot 0.054\%$ of the time of any month

RBER: $BER \leq \frac{280}{L} \cdot \frac{d}{2500} \cdot 5 \cdot 10^{-9}$ in 50% of the time of any month.

A standard hop with a length of approximately 50 km results in an SES allocation of around 0.001% of a month (≈ 25 s).

A digital link is designated unavailable, if the BER exceeds 10^{-3} or if synchronization is lost for more than 10 consecutive seconds. Unavailability of digital radio links is therefore of major concern only for systems operating above 10 GHz, where rain attenuation is a dominant factor. Unavailability objectives for such systems, which mainly form a part of national networks belonging to local and medium-grade circuits have not yet been recommended by CCIR. Planning of links operating above 10 GHz therefore must be based on provisional values for national links, ranging from 0.002% to 0.008% per hop.

Degradation Model for a Radio Link

A wanted radio signal received at a radio relay station is degraded by several influences (**Fig. 2**). The three main detrimental effects on the wanted signal are

- attenuation,
- distortion and
- interference.

Interference can be caused by signals with the same carrier frequency or by signals from adjacent carrier frequencies with the same or orthogonal polarization.

The wanted signal is received at the input of a radio receiver together with the sum of interfering signals. For planning purposes all these interfering signals are modeled into one effective noise power. Outage occurs if the ratio of the wanted signal power to the effective noise power is below a certain limit, which is specific for a given modulation format. Conversely, it is possible to deduce the permissible individual interference contributions from this relation.

In the case of cochannel interference the effective interfering power level depends only on the external isolation mechanism, such as the cross-polar dis-

CCIR Recommendation		*High grade* Rec. 594 Rec. 557	*Medium grade* Rep. 1052				*Local grade* Rep. 1053
Allocation		2500 km 4%	① 280 km 0.45%	② 280 km 2%	③ 50 km 2%	④ 50 km 5%	15%
Severely errored seconds		0.004%	0.0004 %	0.002 %	0.002 %	0.005 %	
10^{-3}	fading	0.050%	0.0056 %	0.0055%	(0.0125)%	(0.0125)%	0.005 to 0.015%
	total	0.054%	0.006 %	0.0075%	(0.0145)%	(0.0175)%	
Degraded minutes 10^{-6}		0.4 %	0.045 %	0.2 %	0.2 %	0.5 %	0.5 to 1.5%
Errored seconds		0.32 %	0.036 %	0.16 %	0.16 %	0.4 %	0.4 to 1.2%
Residual *BER*		5×10^{-9}					10^{-10} to 10^{-7}
Unavailable seconds		0.3 %	(0.033)%	(0.03 to 0.07)%	(0.03 to 0.07)%	(0.07 to 0.17)%	0.08 to 1%

Table 2. Performance and availability objectives of CCIR

crimination (XPD) and angular discrimination of the antennas. Discrimination of all filters in the signal path (channel branching filters, IF filter, roll-off filters) plays an important role in the suppression of adjacent channel interference.

Main Sources of Interference

Each receiver in a digital radio relay network is exposed to a number of interfering signals which can degrade the transmission quality (**Fig. 2**).

- *Intra-system interference*
is generated within a radio channel by *thermal receiver noise, system imperfections* and *echo distortions*. Since thermal noise is an important effect, other effects are often related to the receiver *BER*-curve as a function of the *S/N*.

Degradation due to system imperfections is typically about 1 dB at a *BER* of 10^{-3}, but may be more at a *BER* of 10^{-11}. Echo distortions due to reflections from buildings or terrain, and due to double reflections within the RF-path (antenna, feeder) cannot be neglected in higher-order QAM systems.

- *Interchannel interference* (**Fig. 3**)
of a transmission channel is caused by parallel-operating *cross-polar cochannels* and *co-/cross-polar adjacent channels*. Because of the demand for a more efficient utilization of the RF band, interchannel interference may have an important influence on bit error performance. Typically, a 1-dB degradation of

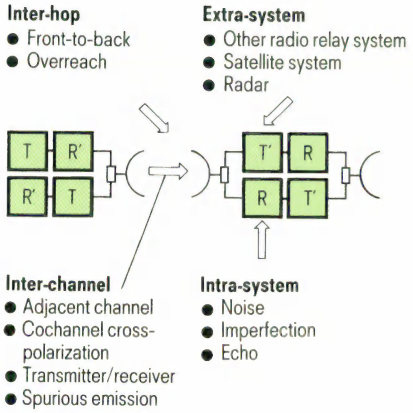
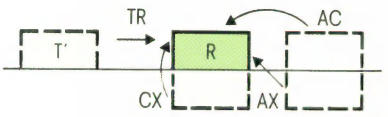


Fig. 2 Main sources of RF interference



AC Adjacent channel, co-polar
AX Adjacent channel, cross-polar
CX Cochannel, cross-polar
TR Transmitter/receiver of innermost channels

Fig. 3 Interchannel interference

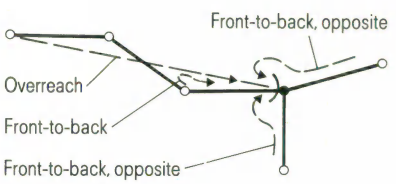


Fig. 4 Inter-hop interference

the *S/N* is permitted, but higher degradations can be accepted, if the design objectives are met. Further interference can occur between transmitters and receivers of the innermost channels at the center gap. Since this type of interference can be suppressed by proper filtering, the resulting degradation should be negligibly small.

- *Inter-hop interference* (**Fig. 4**)
can occur due to front-to-back or nodal interference from both *adjacent hops*, and due to *overreach* interference. The signal-to-interference ratio (*S/I*) is determined by the angular discrimination of antennas and can decrease during fading. Careful route and frequency planning is necessary in order to keep the degradation smaller than 1 dB.

- *Extra-system interferences*
can be caused by other digital or analog radio channels or satellite channels using the same RF band or by out-of-band emissions from other radio systems (e.g. radar). A separate degradation budget is not provided for this kind of interference.

Effect of fading on interference

Fading model

For path planning purposes it is sufficient, as the first step in design, to calculate each hop for two marginal performance criteria:

- *normal condition*
BER = 10^{-10} to 10^{-11} in 50% of the time

- *outage condition*
$BER = 10^{-3}$ in about 0.001% of the time.

A fading model has to be applied, since the threshold objective ($BER = 10^{-3}$) is determined by fading. Different fading of the wanted signal and interfering signal due to selective fading or as a result of different propagation paths has to be taken into account. Three fading models are considered. They all have the same total fading depth (A) – equal to the flat fading margin of the system – but different selectivity:

- *Non-dispersive fading model*
(rain attenuation, obstruction loss).
- *Moderate dispersion model*
representing very frequent two-path fading with weak or moderate dispersion of $\tau \leq 1$ ns (τ is the two-path delay difference). The influence of dispersive amplitude of fading on the S/N is negligible. Enhancement of adjacent channel interference is small. Depolarization is moderate (average XPD degradation is assumed).
- *High dispersion model*
is used for extremely dispersive fading (e.g. $\tau = 6.3$ ns). In this case, the effect of selective fading on the S/N and the S/I has to be taken into account. Depolarization is assumed to be strong (lower limit of XPD).

Effect of frequency-selective fading

Apart from causing intersymbol interference, high dispersive fading does not have the same effect on noise and interference as flat fading has. Typically, in comparison with flat fading of the same total fade depth (A),

- the S/N due to noise is improved,
- the S/I due to cochannel interference in the same hop is unchanged,
- the S/I due to adjacent channel interference is degraded and
- the S/I due to cochannel interference from adjacent hops is improved.

This effect of selective fading on interference depends on fading depth (A), symbol duration (T), time delay (τ), channel separation (s), and on the amplitude enhancement due to the adaptive equalizers used.

Table 3 shows examples of the effects of selective distortion on a 35-MBaud system.

Fading behavior	Total fading depth	35	35	35	35	dB
	Delay	6.3	6.3	1	<1	ns
	Notch depth	15	20	25	35	dB
	Flat fading	20	15	10		
	Notch frequency	10	0	0	0	MHz
Improvement of S/I noise and cochannel	No equalization	9	11	3	0	dB
	Amplitude equalization	7	8	2	0	dB
	Ideal equalization	5	7	1	0	dB
Degradation of S/I adjacent channel (40 MHz)	No equalization	5	6	5	0	dB
	Amplitude equalization	5	5	1	0	dB
	Ideal equalization	5	5	0	0	dB

Table 3 Influence of dispersive fading on noise and interference (symbol rate: 35 MBaud)

For planning purposes these effects can be roughly approximated by simple formulas:

- Improvement of S/N and S/I, cochannel (adjacent hop)

$$\Delta A \approx 0.7 \cdot A \cdot \frac{\tau}{T}$$
$$\approx 0 \quad \text{(moderate dispersion model)}$$
$$\approx \frac{A}{6} \quad \text{(high dispersion model)}$$

- Degradation of S/I, adjacent channel (separation s in MHz)

$$\Delta A \approx 4 \cdot 10^{-4} \cdot A \cdot s^2 \cdot \frac{\tau}{T}$$
$$\approx 10^{-5} A \cdot s^2 \quad \text{(moderate dispersion model)}$$
$$\approx 10^{-4} \cdot A \cdot s^2 \quad \text{(high dispersion model).}$$

No correction is assumed in the case of cochannel (cross-polar) interference in the same hop.

Effect of uncorrrelated fading

The wanted and interfering signal may experience different fading depth if they propagate along different paths.

Differing fading depths will occur in different hops, when both signals have completely different propagation paths (e.g. for opposite front-to-back interference, shown in **Fig. 4**). Here the full fading depth (A) has to be considered for multipath fading and rain attenuation.

This may also occur in the same hop, when both signals are transmitted from different antennas. Different flat fading (due to ducts or diffraction loss) cannot be eliminated by diversity reception. A correction of about 5 to 15 dB has to be provided depending on the path conditions.

Different fading is also possible when both signals have nearly the same propagation path, but both transmitting antennas are separated (e.g. normal front-to-back or overreach interference). In this case the full fading depth is considered for multipath fading (worst case), but no fading difference is assumed for rain attenuation.

A fading correction by automatic regulation of transmitter power as proposed in [2] can reduce the fading effects by about 10 to 15 dB.

Cross-polar discrimination during fading

Cross-polar discrimination is widely used to improve the S/I of inter-channel interference. The XPD_o of a path during normal conditions is determined by the XPD of both antennas in the bore-sight $\left(\pm \frac{\alpha_o}{2}\right)$. Depolarization during multipath fading depends on the XPD behavior of the antennas, echo delay and fading depth (A) of the wanted signal. Measurements showed a simple relationship of $XPD_m = C - A$ with $C = 35$ to 55 dB. Assuming an average value of 49 dB and a lower limit (90%) of 44 dB, as recently measured [3], the XPD of the hop during multipath fading is

$$XPD = -10 \log\left(10^{-\frac{XPD_o}{10}} + 10^{-\frac{XPD_m}{10}}\right)$$

with

$XPD_m = 49\ \text{dB} - A$ (average) and

$XPD_m = 44\ \text{dB} - A$ (lower limit).

The XPD of a hop during rainfall is

$$XPD = -10 \log\left(10^{-\frac{XPD_o}{10}} + 10^{-\frac{XPD_r}{10}}\right)$$

with

$XPD_r = 15\ \text{dB} + 30 \log f(\text{GHz}) - 20 \log A$ (average)

$XPD_r = 9\ \text{dB} + 30 \log f(\text{GHz}) - 20 \log A$ (lower limit)

as proposed in CCIR Report 338. It should be noted that, according to this

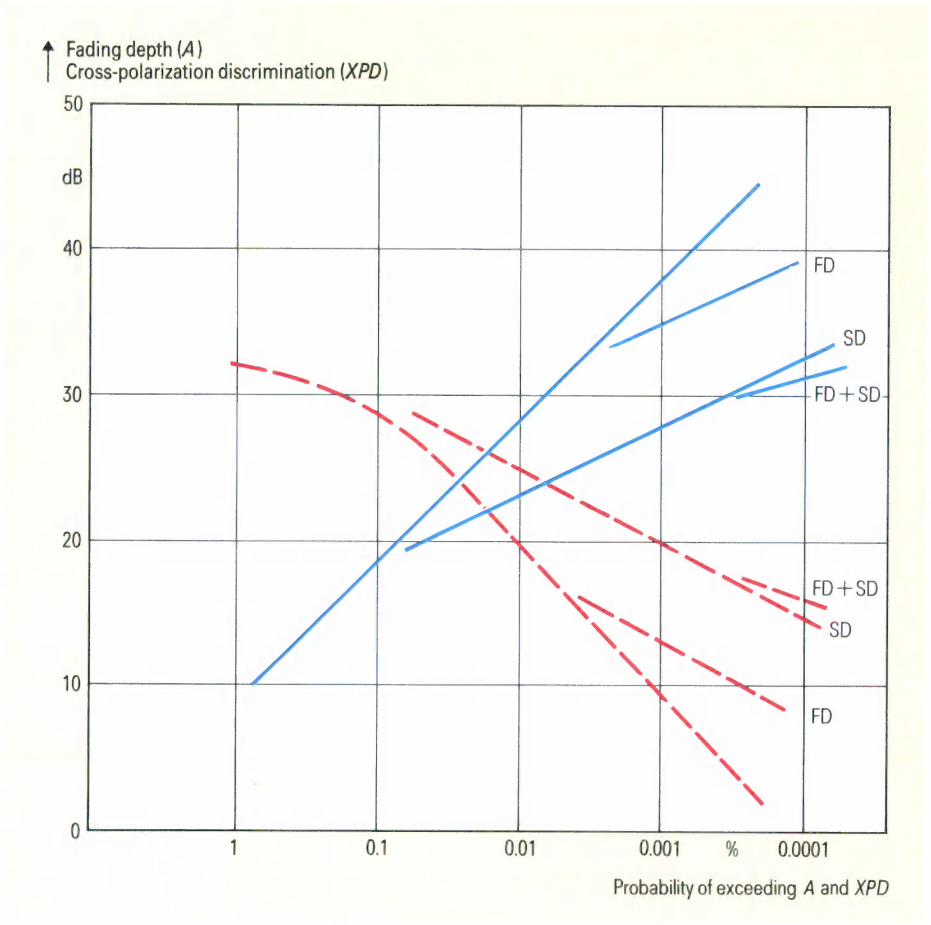


Fig. 5 Typical distributions of fading (*A*) and cross-polar discrimination (*XPD*) during multipath propagation

relationship, intensive rainfall can cause depolarization at frequencies below 10 GHz, although attenuation is small.

A cross-polarization interference canceller (XPIC) improves an insufficient *XPD* of antenna and hop by cancellation of the interference from a cross-polar cochannel.

Diversity reception is very effective in the case of depolarization due to multipath fading, since the probability of heavy fading and depolarization is reduced in this way. Thus, cross-polar cochannel operation of 16-QAM systems can be achieved without applying an XPIC, at least with the exception of very unfavorable hops.

Multipath fading probability

Multipath fading occurrence

The fading depth statistic depends on many factors, such as climate, terrain, hop length, and frequency. Empirical formulas allowing the calculation of the fading probability in the worst month are contained in CCIR Report 338 for various climatic conditions. The most frequently applied formulas are:

$$p = 1.4 \cdot 10^{-8} \cdot f \cdot d^{3.5} \cdot 10^{-A/10}$$

which is suitable for temperate conditions in some European countries and

$$p = k \cdot 10^{-5} \cdot s^{-1.3} \cdot f \cdot d^{3} \cdot 10^{-A/10}$$

for conditions found in the USA, suitable for a wide range of climate (k = 1 to 4.1) and terrain (s = 6 to 47 m).

In these formulas, p is the probability of exceeding the fading depth (A) in dB at a single frequency (f) in GHz on a hop having a length (d) in km with a terrain roughness (s) in m. The corresponding fading depth in $p = \frac{d}{2500} \cdot 0.054\%$ of a month is:

$$A = 38.8\ \text{dB} + 10 \log \frac{f}{6.7} + 25 \log \frac{d}{50}$$

and

$$A = 48.8\ \text{dB} + 10 \log \frac{f}{6.7} + 20 \log \frac{d}{50} - 13 \log \frac{s}{6} + 10 \log k.$$

Improvement by diversity reception

Diversity reception reduces the probability of exceeding a given fading depth. Empirical formulas for calculating the improvement factor (I) are discussed in CCIR Report 338. Used frequently are:

$$I = 1 + 12 \cdot 10^{-4} \cdot \Delta h^2 \cdot f \cdot d^{-1} \cdot 10^{\frac{A}{10}}$$

for space diversity and

$$I = 1 + 0.08 \cdot \Delta f \cdot f^{-2} \cdot d^{-1} \cdot 10^{\frac{A}{10}}$$

for frequency diversity.

Due to diversity reception fading depth (in the same percentage of time) decreases for space diversity to

$$A_D = \frac{A}{2} - 5 \log \frac{12 \cdot \Delta h^2 \cdot f}{10^4 d} = \frac{A}{2} + 9\ \text{dB} + 5 \log \frac{d}{50} - 5 \log \frac{f}{6.7} - 10 \log \frac{\Delta h}{10}$$

and for frequency diversity to

$$A_D = \frac{A}{2} - 5 \log \frac{0.08 \cdot \Delta f}{f^2 d} = \frac{A}{2} + 14\ \text{dB} + 5 \log \frac{d}{50} + 10 \log \frac{f}{6.7} - 5 \log \frac{\Delta f}{40}$$

for $I \gg 1$ where

- A Fading depth without diversity (dB),
- Δh Height separation (m),
- Δf Frequency separation (MHz),
- d Hop length (km) and
- f Frequency (GHz).

In a multi-hop (m), multi-channel (n+1) switched system the improvement due to frequency diversity is reduced by a factor

$$c \approx \sqrt{m} \left(1 + \frac{1}{2} \sum_{i=1}^{n-1} \frac{1}{i}\right)$$

If both space diversity and n+1 switching are applied, a multiplication of both independent improvement factors can be expected. Thus, the fading depth is

$$A_D = \frac{A}{3} - \frac{10}{3} \log \left(\frac{10^{-4} \cdot \Delta f \cdot \Delta h^2}{d^2 \cdot f \cdot c}\right) = \frac{A}{3} + 15\ \text{dB} + \frac{20}{3} \log \frac{d}{50} + \frac{10}{3} \log \frac{f}{6.7} - \frac{10}{3} \log \frac{\Delta f}{40} - \frac{20}{3} \log \frac{\Delta h}{10} + \frac{10}{3} \log c.$$

The principal behavior of fading distributions and of degraded *XPD* with and without diversity is shown in **Fig. 5**. It should be noted that in both cases (with and without diversity) the *XPD* distributions follow the inverse fading distribution.

Rain attenuation

The calculation method used is based on CCIR Reports 563, 338 and 721. It is based on a rainfall intensity for 0.01% of the year. Typical values can be found in the tables of CCIR Report 563, if measured distribution of rainfall is not available. The rain attenuation in dB/km (γ) for the frequency used can be evaluated using figures or formulas given in CCIR Report 721. The effective hop length (d_{eff}) – taking into account the limited diameter of rain zones – can be estimated by $d_{\text{eff}} = \dfrac{d}{1+0.045\,d}$.

The path attenuation exceeded 0.01% of the time is

$A_{0.01} = \gamma \cdot d_{\text{eff}}$.

Attenuation for percentages smaller than 0.01% of the time can be estimated from

$A_p = 0.22 \cdot A_{0.01} \cdot p^{-0.33}$.

The probability in % (p) of exceeding a rain attenuation in dB (A) is then

$p = \dfrac{1}{98} \cdot \left(\dfrac{\gamma\, d_{\text{eff}}}{A}\right)^3$.

Since this simplified method is mainly based on measured data from temperate climates, care should be exercised in tropical or monsoon rain zones (especially in the calculation of d_{eff}).

Addition of interferences

Interference of the same effective power but from different sources and with different behavior can produce a different *BER*. A simple procedure would be to add all interference sources on a power basis. However, measurements have shown that this method is too pessimistic in the case of a digital or analog (sinusoidal) cochannel interference source, especially when the interference is strong.

This will be the case when cross-polar frequency reuse is applied. The single cross-polar cochannel interference source can be treated more or less as a noise signal having a lower average power of about $k = 2$ to 3 dB.

All other single or multiple interference are summed using power law addition:

$$\frac{S}{N+I} = -10\log\left(10^{-\frac{S/N}{10}} + 10^{-\frac{S/EH}{10}} + 10^{-\frac{S/ES}{10}} + 10^{-\frac{S/AX}{10}} + 10^{-\frac{S/AC}{10}} + 10^{-\frac{S/CX}{10}} + 10^{-\frac{S/AH}{10}} + 10^{-\frac{S/OH}{10}}\right)$$

where

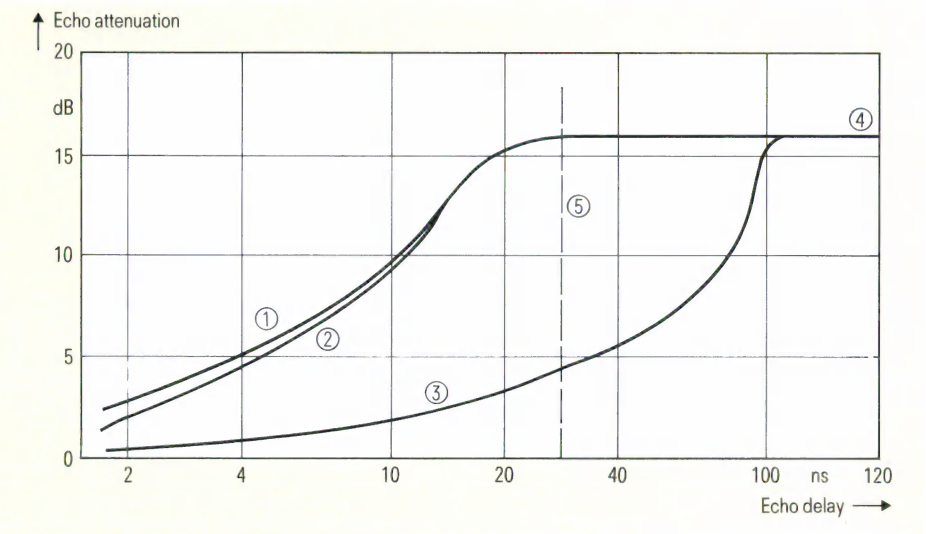
N	noise, including system imperfections
EH	cochannel echo from terrain within the hop
ES	cochannel echo within the system
AX	adjacent channel, cross-polar
AC	adjacent channel, co-polar
CX	cochannel, cross-polar
AH	adjacent hop
OH	overreach hop

The calculation rules for the most important forms of interference are summarized in the following section. The signal-to-interference ratios are estimated for the two conditions mentioned above: normal ($BER = 10^{-11}$, 50% of time) and threshold ($BER = 10^{-3}$). The total S/I should not exceed the typical values listed in **Table 4**.

	4 QAM (PSK)	16 QAM	64 QAM*	256 QAM*
$S/(N+I)$, $BER = 10^{-11}$	19 dB	28 dB	34 dB	41 dB
$S/(N+I)$, $BER = 10^{-3}$	11 dB	18 dB	24 dB	30 dB

* Forward error correction is assumed

Table 4 Typical S/I values for BER of 10^{-11} and BER of 10^{-3}



① Without equalizer
② With amplitude slope equalizer
③ With transversal equalizer (7 taps symmetrical)
④ Cochannel interference for 16 QAM
⑤ Symbol duration of the system

Fig. 6 System outage ($BER = 10^{-3}$) due to an echo distortion in the DRS 140/16 QAM

Calculation rules for major contributions of interference

S/N due to thermal receiver noise and imperfections

$S/N_o = C_o - 10\log kT_o - F - 10\log B - \Delta$

$S/N = S/N_o - A + \delta A$

where

$10\log kT_o = -114$ dBm/MHz

F	Noise figure (dB)
B	Receiver noise bandwidth (MHz) (= symbol rate, if equally distributed $\cos^2$ roll-off)
Δ	Degradation by system imperfections (dB)
A	Fading depth (dB)
C_o	Normal receiver input level
δA	Correction for high dispersive fading

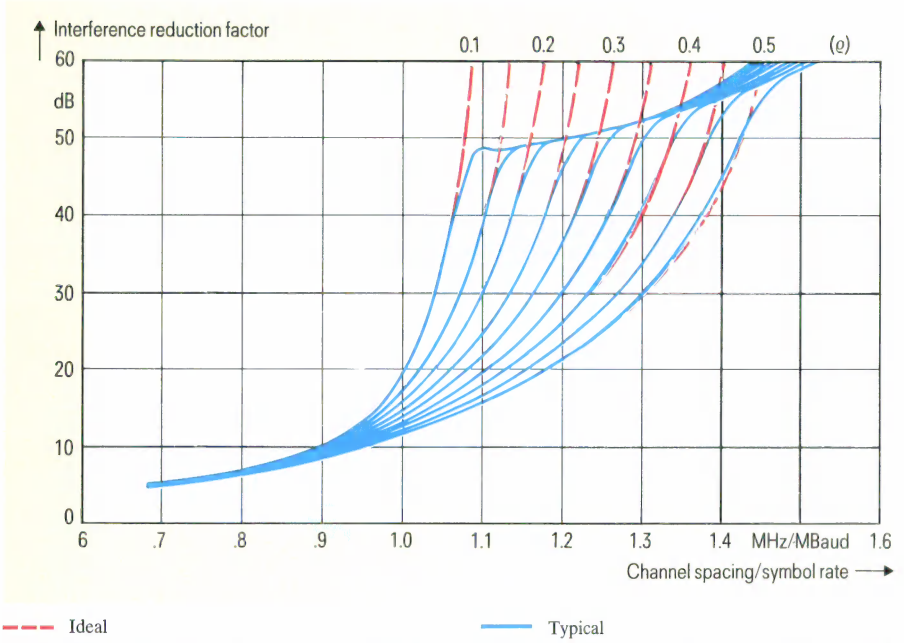
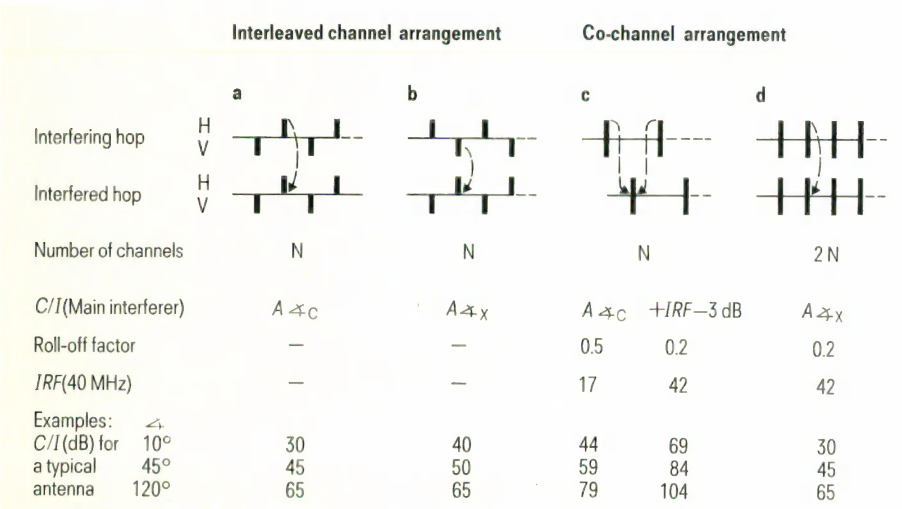


Fig. 7 Ideal and typical adjacent channel interference of QAM systems for different roll-off factors (ϱ)



	a	b	c		d
Number of channels	N	N	N		2 N
C/I(Main interferer)	A_C	A_X	A_C	$+IRF-3$ dB	A_X
Roll-off factor	—	—	0.5	0.2	0.2
IRF(40 MHz)	—	—	17	42	42
Examples: C/I(dB) for a typical antenna 10°	30	40	44	69	30
45°	45	50	59	84	45
120°	65	65	79	104	65

Fig. 8 Examples of inter-hop interference for DRS 140/16 QAM

Cochannel echoes within the hop

The S/I due to a reflection from terrain or building within the hop having a certain echo amplitude (r) is

$$S/EH_o = -20 \log r$$

$$S/EH = S/EH_o - A.$$

Echo delays can vary widely from about 0.1 to 1 ns (ground reflections) to more than 1 ns (reflection near the antennas or from distant buildings). As can be seen from **Fig. 6**, echoes with a delay (τ) exceeding the symbol duration (T) of a system can be treated as cochannel interference. Smaller delays have less influence.

A considerable improvement is obtained by using a transversal equalizer, but this depends on the τ/T ratio and the number of equalizer taps. Diversity reception is only effective during fading.

Cochannel echoes within the system

Echoes caused by double reflection in the system (*long line effect*) have very long delays. In an air-filled waveguide with a certain length (L, in m), the delay (τ, in ns) is about

$$1.3 \cdot \frac{2L}{0.3}.$$

In this case, diversity reception is ineffective. Improvement due to a transversal equalizer is small (**Fig. 6**), depending on by the number of taps. The S/I is given by the sum of both return losses (A_r) and does not decrease during fading.

$$S/ES_o = A_{r1} + A_{r2}$$

$$S/ES = S/ES_o.$$

Adjacent channel, cross-polar interference

Adjacent channel cross-polar interference is mainly determined by the interference reduction factor (IRF) due to filter response and spectrum shapes –also called *net filter discrimination* (NFD) – and the cross-polar discrimination (XPD).

$$S/AX_o = IRF - 3\,\text{dB} + XPD_o$$

$$S/AX = IRF - 3\,\text{dB} - 10 \log \left(10^{-\frac{XPD_o}{10}} + 10^{-\frac{XPD}{10}}\right) - \Delta A.$$

IRF curves are shown in **Fig. 7**. For example, the calculated IRFs of a 16-QAM system (symbol rate/channel separation = 1.13) with roll-off factors of 0.5 and 0.19 are 17 and 39 dB, respectively, whereas the measured IRFs were 17 and 42 dB, respectively. XPD_o is the sum of cross-polar discrimination of both antennas. XPD is the degraded cross-polar discrimination during fading described in the section on the effect of fading on interference. The fading difference (ΔA) can be calculated in accordance with the section, "Effect of frequency-selective fading."

Adjacent channel, co-polar interference

This type of interference can be suppressed sufficiently by suitable filtering (IRF, roll-off factor) and should not lead to degradation.

The fading difference (ΔA) is calculated as above:

$$S/AC_o = IRF - 3\,\text{dB}$$

$$S/AC = S/AC_o - \Delta A.$$

Cochannel, cross-polar interference

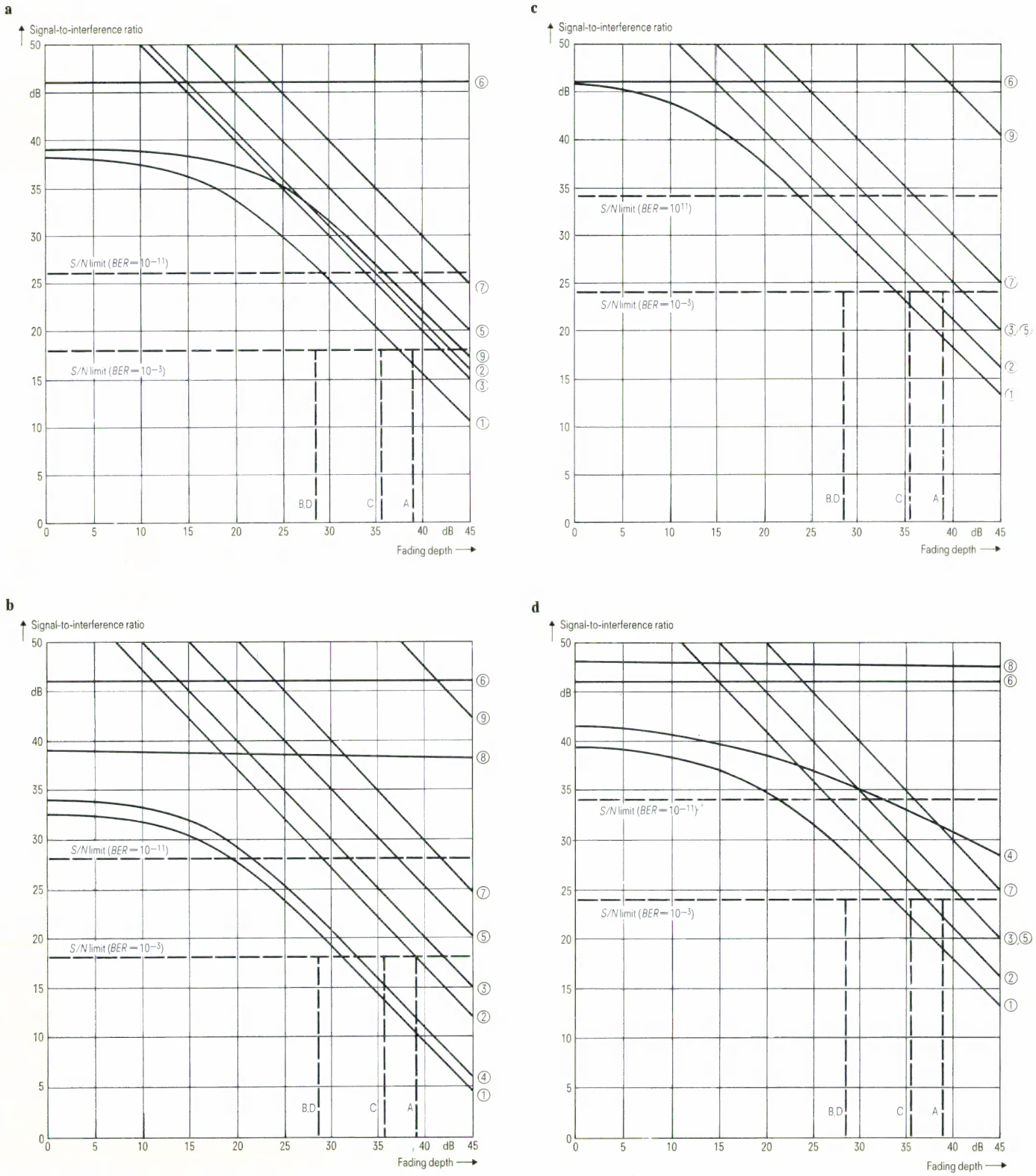
Cochannel, cross-polar interference is important when cross-polar frequency reuse in a hop is applied with the aim of doubling the band utilization or to facilitate planning at network nodes.

$$S/CX_o = XPD_o$$

$$S/CX = -10 \log \left(10^{-\frac{XPD_o}{10}} + 10^{-\frac{XPD}{10}}\right) + D.$$

XPD_o is the sum of cross-polar discrimination of both antennas. Formulas for calculating the XPD of a hop during fading are given above in the section on the effect of fading on interference.

D is the cochannel improvement factor (in comparison with a noise-like interference source). A D of 2 dB can be used



① Total *S/I*
② Noise
③ Adjacent hop
④ Cochannel, cross-polar
⑤ Echo hop (terrain)
⑥ Echo system (long line)
⑦ Overreach decoupling
⑧ Adjacent channel, co-polar
⑨ Adjacent channel, cross-polar

A Without diversity
B With space diversity (10 m)
C With frequency diversity (40 MHz, 7 + 1)
D With space and frequency diversity

Fig. 9 Calculated typical *S/I* as a function of fading depth (moderate dispersion model)

a DRS 140/6700/16 QAM with roll-off factor of 0.5 (interleaved channel arrangement)
b DRS 140/6700/16 QAM with roll-off factor of 0.2 (cochannel arangement)
c DRS 140/6200/64 QAM with roll-off factor of 0.4 (interleaved channel arrangement)
d DRS 140/6200/64 QAM with roll-off factor of 0.25 (cochannel arrangement)

Channel separation	0	40	80	MHz
DRS 140/16-0.5 → FM 2700	9	37	>100	dB
DRS 140/16-0.5 ← FM 2700	9	61	>100	dB
DRS 140/16-0.2 → FM 2700	9	39	>100	dB
DRS 140/16-0.2 ← FM 2700	0	61	>100	dB
DRS 140/16-0.5 → FM 1800	12	52	>100	dB
DRS 140/16-0.5 ← FM 1800	0	68	>100	dB
Channel separation	0	29.65	59.3	MHz
DRS 140/64-0.4 → FM 1800	10	46	>100	dB
DRS 140/64-0.4 ← FM 1800	0	61	84	dB
DRS 140/64-0.25 → FM 1800	10	52	>100	dB
DRS 140/64-0.25 ← FM 1800	9	61	84	dB
DRS 140/64-0.4 → FM TV	26	78	>100	dB
DRS 140/64-0.4 ← FM TV	9	56	84	dB

Table 5 Examples of interference between DRS and FM systems

as a rather pessimistic approximation. The fading difference is negligible when both orthogonal channels use the same transmitting antenna. If not, a correction for uncorrelated fading of about 5 to 15 dB is required.

Adjacent hop interference

Adjacent hop interference depends on the angular discrimination (front-to-back ratio) of antennas and on the correlation of fading between the wanted and interfering signal. Since it is difficult to estimate the specific fading difference, the worst case is assumed.

Fading correction by automatic regulation of transmitting power, which may become an effective method of alleviating inter-hop interference problems in the future, has not been considered here.

In principle, adjacent hop interference can arise from cochannel and adjacent channel co-polar and cross-polar signals. Which type of interference dominates depends on the channel arrangement used:

Interleaved channel arrangement

- cochannel co-polar, (adjacent channel cross-polar) (**Fig. 8a**).

$$S/AH_0 = A_{\measuredangle c} \pm \Delta P$$
$$S/AH = S/AH_0 - A.$$

- cochannel cross-polar, adjacent channel co-polar (**Fig. 8b**)

$$S/AH_0 = -10 \log\left(10^{-\frac{A_{\measuredangle x}}{10}} + 10^{-\frac{A_{\measuredangle c} + IRF - 3\,\mathrm{dB}}{10}}\right) \pm \Delta P$$
$$\approx A_{\measuredangle x} \pm \Delta P$$
$$S/AH = S/AH_0 - A.$$

Cochannel arrangement

- adjacent channel (no cochannel interference) (**Fig. 8c**).

$$S/AH_0 = A_{\measuredangle c} + IRF\,3\,\mathrm{dB}$$
$$S/AH = S/AH_0 - A$$

- cochannel co-polar, adjacent channel co-polar (and cross-polar)

$$S/AH_0 = -10 \log\left(10^{-\frac{A_{\measuredangle x}}{10}} + 10^{-\frac{A_{\measuredangle c} + IRF - 3\,\mathrm{dB}}{10}}\right)$$
$$S/AH = S/AH_0 - A, \text{ where}$$

$A_{\measuredangle c}$ Co-polar angular discrimination of antenna
$A_{\measuredangle x}$ Cross-polar angular discrimination of antenna
A Fading depth
ΔP Difference of receive level between wanted and interfering signal (due to different transmitter power, antenna gain, hop length).

In **Fig. 8** four typical situations of interference at a nodal point (angular decoupling for 30°, 60° and 120°, co-polar and cross-polar is assumed) are compared for a 16-QAM system with two different roll-off factors of 0.5 and 0.2. The comparison shows that very small angles can be realized at network nodes using a cochannel arrangement with a large *IRF*.

Overreach hop interference

$$S/OH_0 = A_{\measuredangle 1} + A_{\measuredangle 2} \pm \Delta P$$
$$S/OH = S/OH_0 - A.$$

If the interference is cross-polar, the smaller sum of both co-polar and cross-polar angular discrimination has to be taken. Calculation of fading difference is not a simple task, because fading of the the wanted signal as well as overreach of the interfering signal (smaller obstruction loss during superrefraction) may decrease the *S/N*. In the case of the nearest interference from the third hop, the full fading depth (A) can be assumed.

Interference from and into analog systems

Table 5 shows some examples of the *IRF* between DRS and FM systems. The *S/I* can be calculated by adding the RF decoupling (*XPD*, angular discrimination, different path loss and transmitter power) to the corresponding *IRF*.

Nominal loading is assumed for FM systems. It should be mentioned that other effects (e.g. squelch, pilot) must also be checked, when compatible operation of FM and DRS systems is planned.

Examples of calculated *S/I* as a function of fading

Typical *S/I* curves calculated for a *moderate dispersion* fading model are presented in **Fig. 9**. The resulting $S/(N+I)$ is compared with the permissible $S/(N+I)$ for *BER*s of 10^{-3} and 10^{-11} and the expected fading depth in a typical hop (NW-Europe, 50 km, 6.7 GHz) for 0.001% of the time, when space diversity, frequency diversity (7 + 1 switching, 40 MHz) and no diversity are applied. The calculation is based on typical system data. The values for terrain echoes (65 dB), long line echoes (46 dB) and overreach decoupling (70 dB) are assumed. Such diagrams provide a very lucid representation of effects of the various kinds of interference on the system over the entire fading and *BER* range.

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[2] US Patent 4004224, Jan. 18, 1977, "Method for Fade Correction of Communication Transmission over Directional Radio Paths."

[3] Rooryck, M.; Fernandez, E.; Delmas, J.; Benoit-Guynod, G.: "Les résultats actuels des mesures propagation à 4 GHz en France." L'Onde Electrique, May 1986, No. 3/67, p. 73

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Narrowband Radio Relay Systems

Narrowband radio relay systems for the transmission of digital signals at the bit rates of 2 and 8 Mbit/s are employed predominantly in medium-haul PTT networks and in private networks. The existing narrowband radio relay systems for analog transmission have now been augmented by an equivalent series of systems for digital transmission in the frequency bands 800, 1800, 7200 and 7500 MHz, as reported in the following article.

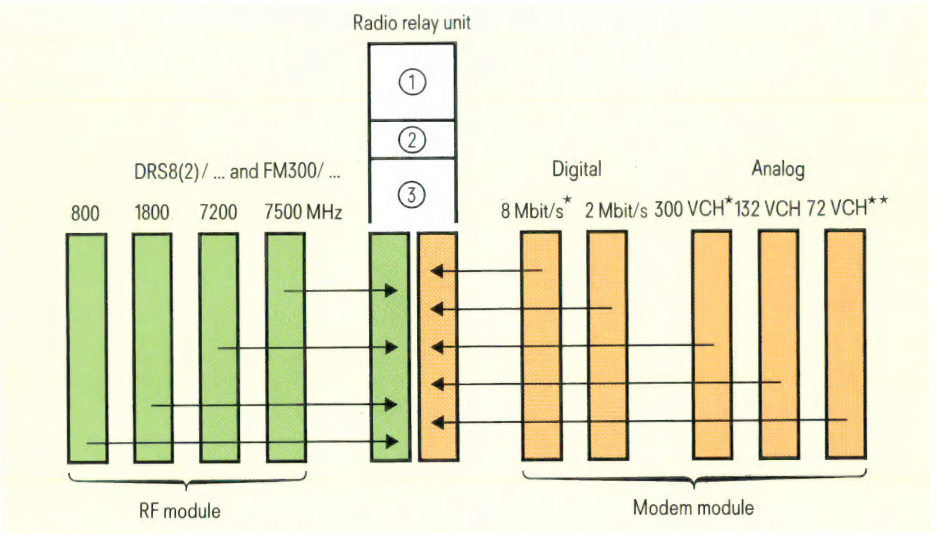
The new series of *digital* narrowband radio relay systems has been designed to incorporate the flexibility, economy and reliability that were a feature of the analog system series [1]. The transmitter and receiver form a compact physical unit. The modular design, partitioning the equipment into easily replaceable radio-frequency (RF) and modem modules with standard interfaces, has made the equipment more readily adaptable to the different radio-frequency bands and transmission capacities (**Fig. 1**). The modulated transmit signal is generated directly in the radio-frequency band by frequency modulation of a power oscillator. As a result, up-conversion from the intermediate frequency (IF) to the radio-frequency band is eliminated together with the associated sideband filtering.

Since there is generally no need for a multistage power amplifier even in the DRS 2/800 radio relay system, the resultant design is very compact and highly efficient. Moreover, frequency synthesizers in the transmit and receive oscillators enable the radio frequency to be retuned without the need for changing the crystal.

Applying this transmitter concept to digital transmission resulted in the adoption of continuous-phase frequency-shift keying (CPFSK) as the preferred modulation method. This technique is relatively simple to implement, providing even low capacity systems with compact signal spectra and good bandwidth utilization without complex filtering in the IF or RF band. The constant signal amplitude associated with frequency-shift keying also means that there are no special demands on the linearity of the signal path. Frequency-shift keying with incoherent demodulation has, moreover, proved to be a very robust modulation method. The slightly higher signal-to-noise ratio required relative to phase-shift keying (PSK) is more than compensated for by a number of practical, economic and operational benefits.

The narrowband series of systems for digital transmission employs three-level frequency-shift keying by an HDB3-encoded, bandlimited baseband signal.

This technique produces a very simple design for baseband processing and obviates the need for a scrambler. It permits direct transmission of a service channel in its original band (300 to 3400 Hz) simply by superimposing the channel on the baseband signals. Furthermore, the transmission quality is very simple to monitor.



* Not provided for the 800-MHz RF band

** Not provided for the 7200 and 7500-MHz RF bands

① Mounting system
② Service channel equipment
③ Voltage converter

DRS Digital radio relay system
FM Frequency modulation
RF Radio frequency
VCH Voice channel

Fig. 1 Possible system configurations for digital or analog transmission

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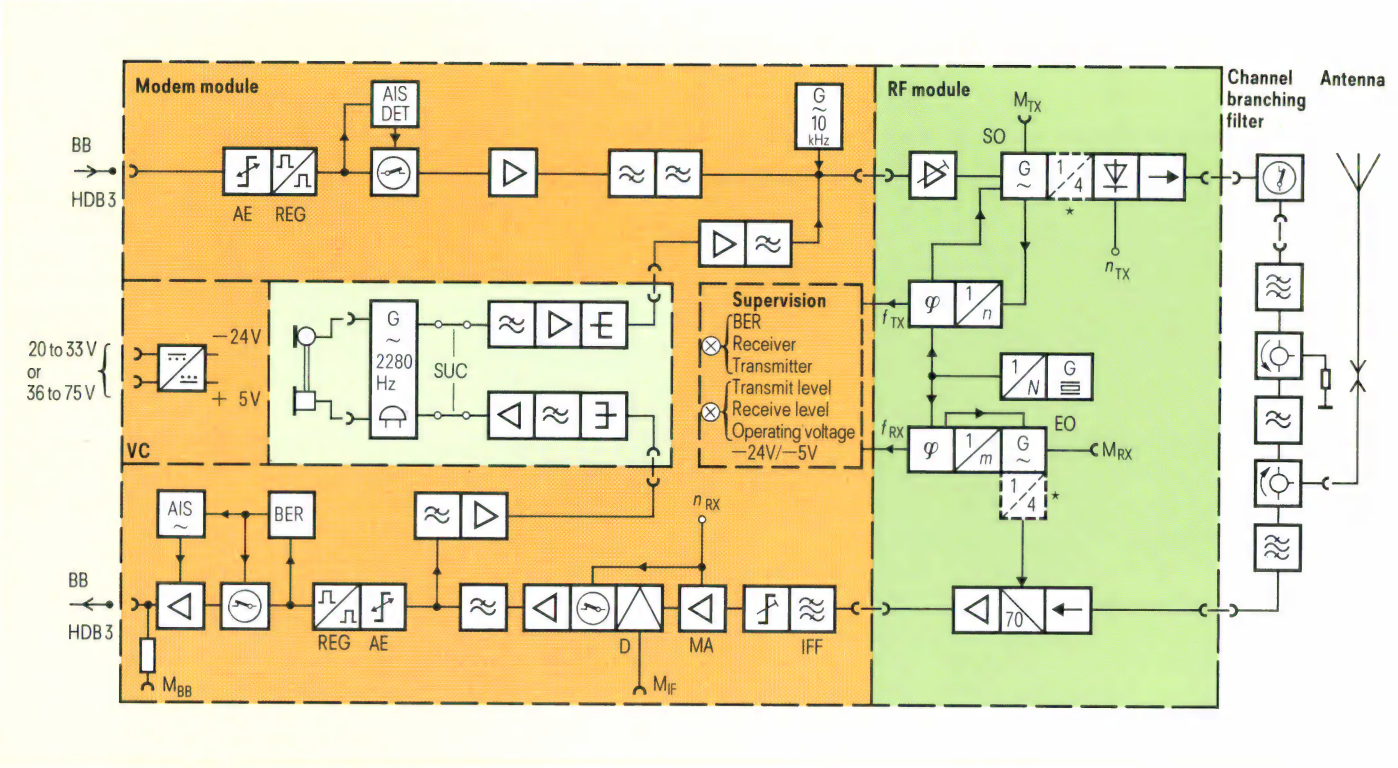


* Frequency quadrupler for 7200 and 7500 MHz only

AE	Attenuation equalizer	IF	Intermediate frequency	n_{RX}	Receive power criterion
AIS	Alarm indication signal	IFF	Intermediate frequency filter	n_{TX}	Transmit power criterion
AISDET	AIS detector	MA	Main IF amplifier	REG	Regenerator
BB	Baseband	m	Division factor	RF	Radio frequency
BER	Bit error ratio supervision	M_{BB}	Baseband test jack	RXO	Receive oscillator
D	Demodulator	M_{RX}	Receiver frequency test jack	SUC	Supervisory control interface
f_{RX}	Receiver frequency criterion	M_{TX}	Transmitter frequency test jack	TXO	Transmit power oscillator
f_{TX}	Transmitter frequency criterion	M_{IF}	Intermediate frequency test jack	VC	Voltage converter
G	Generator	N, n	Division factors	φ	Phase comparator
HDB3	HDB3 code (high density bipolar of order 3)				

Fig. 2 Functional diagram of the digital radio relay systems for the radio-frequency bands 1800, 7200 and 7500 MHz

Electrical operation

Fig. 2 shows, as an example, the functional diagram of a complete unit (transmitter and receiver) for transmitting digital signals at 2.048 or 8.448 Mbit/s in the RF bands 1800, 7200 and 7500 MHz.

Transmit section

In the interface circuit the incoming, HDB3-encoded digital signal is automatically raised to a constant level and equalized. The regenerator converts it to two parallel binary signals, one representing the positive, the other the negative pulses in the HDB3 signal. On receipt of an alarm indication signal (AIS) a detector circuit causes the data signals to be interrupted. This prevents the radiation of an unnecessarily wide spectrum with discrete lines. Other periodic signal patterns are prevented from producing interfering line spectra in adjacent RF channels carrying analog signals by the additional provision of carrier energy dispersal with a modulation frequency of 10 kHz.

After regeneration, the baseband signal components are converted back to a pseudoternary HDB3 signal whose signal spectrum is limited by a low-delay low-pass filter. In addition, a high-pass filter suppresses spectral components in the voice-frequency band. The service channel signal and the carrier energy dispersal signal are then inserted.

The baseband signal, thus processed, assembled and leveled, directly modulates a power oscillator operating in the 800-MHz or 1800-MHz band. The three-level nature of the (bandlimited) HDB3-encoded baseband signal is used to produce three-level frequency-shift keying. In the 1800-MHz system, the RF signal is fed directly, with no further amplification, to the transmitter output and is passed from there via an RF switch to the transmit filter of the channel branching filter and on to the antenna. In the radio relay systems for the frequency bands, 7200 and 7500 MHz, the output signal of the power oscillator is raised to the final RF band by a frequency quadrupler. In the 800-MHz system, an RF power amplifier can be employed to raise the system value.

At the output of the transmitter the transmit power is monitored by an RF probe. Any decrease in the transmit power produces an alarm. The transmit frequency is stabilized by the synthesizer principle employing a phase-locked loop (PLL) with a crystal-controlled reference oscillator. The operation of this stabilizing circuit is also monitored.

Receive section

From the antenna the received signal is passed via the receive filter to the

receiver input. In the systems for frequency bands 1800, 7200 and 7500 MHz the RF signal is translated to IF directly by the down-converter. In the 800-MHz system, a low-noise RF preamplifier is provided to improve the system value. The local oscillator signal required for down-conversion to IF is supplied by the receive oscillator which differs from the transmit oscillator only with respect to its lower power.

The down-converter is followed by an IF preamplifier and an IF filter module. This module provides the necessary IF selectivity and equalizes delay distortion originating in the RF path. A main IF amplifier with a large control range then maintains the IF signal at a constant level. It also furnishes a dc voltage proportional to the input level for use in indicating and monitoring the receive level.

The demodulator translates the modulated IF signal to the baseband. After bandlimiting and attenuation equalization to improve the pulse shape, the (HDB3-encoded) baseband is regenerated, i.e. converted to two binary signals corresponding to the positive and negative pulses, and the timing signal is recovered. In the output amplifier the regenerated binary signals are converted to a standard HDB3 line signal available at the baseband output of the receiver. In addition, a bit error detector checks the baseband signals for code rule violations. This provides continuous quality monitoring of the transmission link. If a preselected bit error rate is exceeded, the signal path is interrupted and an internally generated AIS is inserted.

At the demodulator output the service channel signal is extracted by a low-pass filter and is fed via an isolating amplifier to the service channel output.

The main specifications of the systems described are summarized in the **table**. **Fig. 3** shows typical curves for bit error rate as a function of receiver input level for the various members of the narrow-band system series. These specifications demonstrate the excellent transmission characteristics of these FSK systems and show that the very slight difference in signal-to-noise ratio requirement relative to comparable PSK systems is virtually negligible.

Circuit design features of the RF and modem modules

RF module

The transmitter concept adopted features high efficiency and reliability with a directly modulated power oscillator. This oscillator is designed as an emitter-coupled, voltage-tuned transistor oscillator with a mechanically tunable $\lambda/4$ coaxial circuit as the frequency-determining resonator. A suitable choice of material for the inner and outer conductors keeps frequency instability within limits over the operating temperature range. The electronic tuning for modulation and frequency control is effected by varactor diodes, the tuning characteristic of the modulation diodes being linearized via a suitable network.

The active element in the transmit oscillator is a microwave power silicon transistor. The RF power is extracted from its emitter via a matching network. This is followed by a low-pass filter to improve the harmonic margin. A small portion of the RF signal is fed to the test jack and to the frequency stabilizing circuit.

Fig. 4 shows the principle of frequency stabilization by phase-locked loop (PLL) adopted for the systems operating in the

Digital radio relay system	DRS 2/800	DRS 8(2)/1800	DRS 8(2)/7200	DRS 8(2)/7500
RF data				
Frequency range	790 to 960 MHz	1700 to 1900 MHz	7125 to 7425 MHz	7425 to 7725 MHz
per CCIR Recommendation	–	283-3	385-1	385-1
Separation between transmit and receive frequencies of an RF channel pair	≥30 MHz	119 MHz	161 MHz	161 MHz
Separation between center frequencies of adjacent RF channels	5 MHz	14 MHz	7 MHz	7 MHz
Transmitter				
Transmit power (unit output)	≥1.2 W ≥6 W*	≥1.5 W	≥0.5 W	≥0.5 W
Frequency instability	$7 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	$8 \cdot 10^{-6}$
Receiver				
Noise figure	≤5 dB	≤7 dB	≤8 dB	≤8 dB
Intermediate frequency	70 MHz	70 MHz	70 MHz	70 MHz
Modulation				
Modulation method	CPFSK**	CPFSK**	CPFSK**	CPFSK**
Frequency shift (zero-to-peak)				
2.048 Mbit/s, f_m = 1 MHz	1 MHz	1 MHz	1 MHz	1 MHz
8.448 Mbit/s f_m = 4.2 MHz	–	4 MHz	4 MHz	4 MHz
Baseband interface				
Input and output	CCITT Recommendation G.703		CCITT Recommendation G.703	
Code	HDB3 code		HDB3 code	
Bit rate (bit repetition rate of data signal)	2.048 Mbit/s		2.048 Mbit/s or 8.448 Mbit/s	
Service channel equipment				
Number of voice channels	1 VF service channel			
SC frequency range	300 Hz to 3.4 kHz			
with supervision control (SUC)	300 Hz to 2.6 kHz			
Frequency range of SUC	2.7 to 3.4 kHz			

* With RF amplifier
** CPFSK with carrier energy dispersal
f_m Modulation frequency
RF Radio frequency
CPFSK Continuous-phase frequency-shift keying
SC Service channel

Table Technical data on digital radio relay systems, DRS 2/... and DRS 8/...

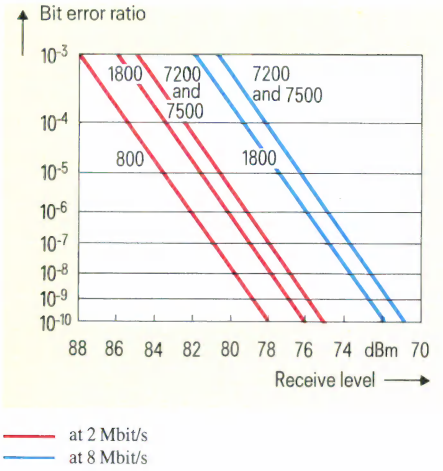
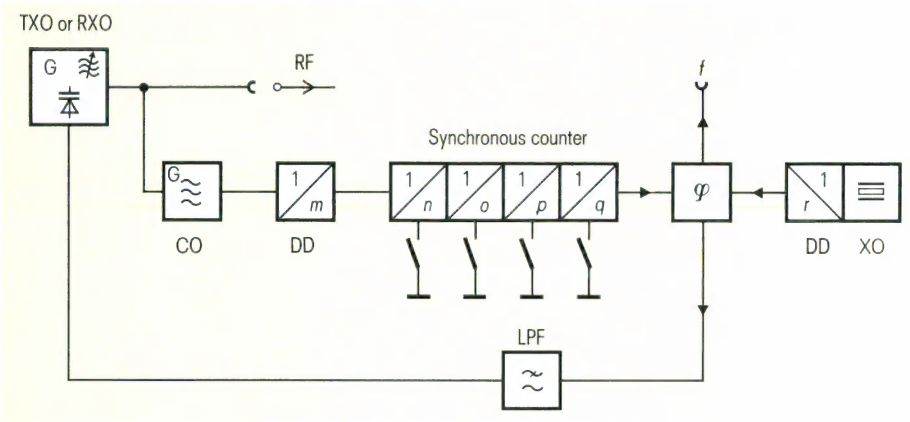


Fig. 3 Bit error ratio as a function of receive level

bands 1800, 7200 and 7500 MHz. The 1.8-GHz signal from the oscillator is reduced by a frequency divider chain to about 2 kHz for transmitter and receiver alike and is compared with a reference signal produced by a crystal oscillator. A control signal derived from the phase difference detected in a phase comparator controls the frequency of the microwave oscillator in such a way as to establish phase lock between the microwave signal and the crystal-controlled reference signal (PLL principle).

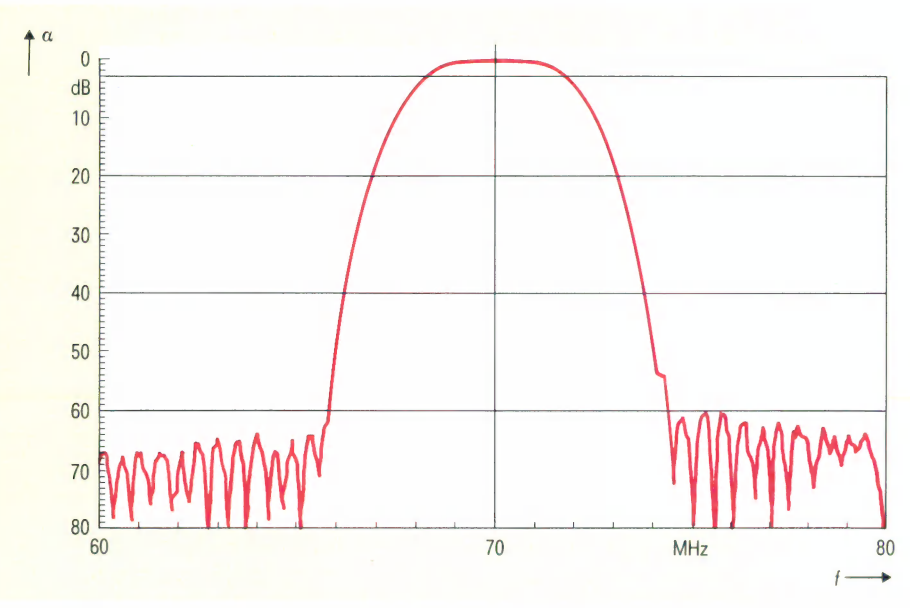
The first circuit in the frequency divider chain is an analog frequency divider. It is designed as a free-running oscillator injection-locked to the 4th harmonic of the power oscillator and thus provides division by a factor of four. The following dividers are integrated digital devices. A slide switch is used to select a division factor corresponding to the required radio frequency. The smallest frequency increment in the 1.8-GHz range of the master oscillator is 250 kHz. Operation of the phase-locked loop is supervised via a monitoring signal produced by the phase comparator when the loop is locked.

Since the frequency stabilizing circuit in the 800-MHz system operates in a lower frequency band, it does not require the analog frequency divider and consists only of the digital divider devices. In this system, moreover, the circuit is employed primarily to stabilize the frequency of the receive oscillator. The transmit frequency is stabilized by another PLL circuit which keeps the frequency difference between transmit and receive oscillator signals constant. Here, the smallest selectable frequency increment is 500 kHz.



CO	Carrier-injected oscillator	*m, n, o, p, q, r*	Division factors
DD	Digital frequency divider	XO	Crystal oscillator
f	Frequency supervision	RXO	Receive oscillator
G	Generator	TXO	Transmit oscillator
LPF	Low-pass filter	φ	Phase comparator

Fig. 4 Phase-locked loop (PLL) of the transmit and receive oscillators



a Attenuation *f* Frequency

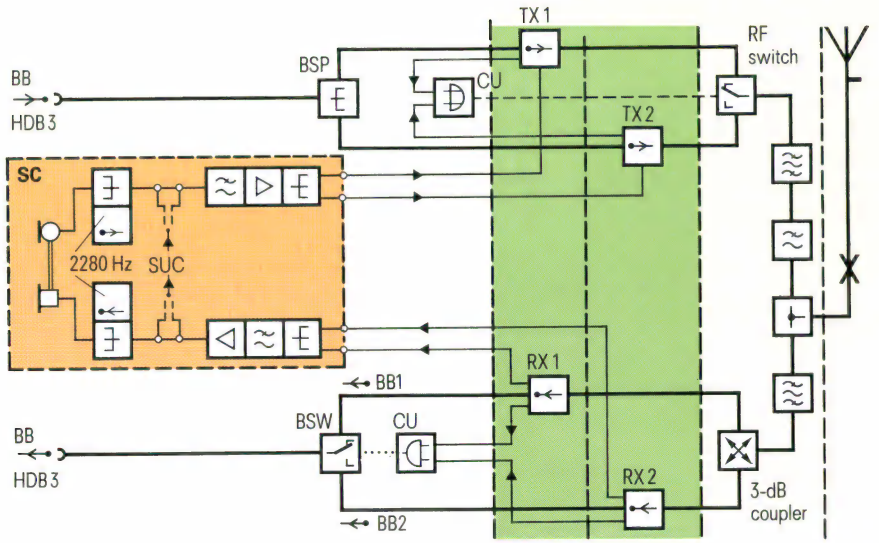
Fig. 5 Attenuation curve of the SAW (surface acoustic wave) IF filter for 2 Mbit/s or 132 voice channels

Modem module

Until now, IF selectivity in narrowband radio relay systems required the use of complex LC filters which involved considerable effort in alignment and temperature compensation. The radio relay systems described here are the first in which surface acoustic wave (SAW) filters have been employed [2, 3].

The computer-aided design procedure employed for these SAW filters converts the required electrical characteristics directly to a photolithographically defined surface structure. This produces an extremely precise filter characteristic of high stability. Filter alignment is completely eliminated. **Fig. 5** shows the typical attenuation curve of a SAW filter employed both for digital transmission at 2 Mbit/s and for the analog transmission of 132 voice channels.

The main IF amplifier comprises four amplifier stages employing negative feedback and having two series-connected PIN diodes inserted between them as electronically controllable attenuators. A rectifier circuit is at the output of the IF amplifier to derive the actual value used in the control circuit for stabilizing the IF level. Comparison with the reference value determines the



BB	Baseband	RX	Receiver
BSW	Baseband switch	SC	Service channel equipment
BSP	Baseband splitter	SUC	Supervisory control interface
CU	Control unit	TX	Transmitter
HDB3	HDB3 code (high density bipolar of order 3)		

Fig. 6 Functional diagram of protection switching equipment

control current for the PIN diodes in the attenuators. The amplifier also employs a linearizing network to generate a voltage proportional to the IF input level for the purpose of indicating and monitoring the receive level.

As in the analog system, the IF signal modulated with a 2-Mbit/s data stream is demodulated using a demodulator operating on the PLL principle. If an 8-Mbit/s signal is transmitted, a balanced detector is required on account of the larger bandwidth.

Supplementary equipment

The radio relay unit can be augmented by a service channel equipment for transmitting a voice-frequency signal in its original band (300 to 3400 Hz). A collective calling equipment provides access to all associated radio relay stations. It is also possible to connect supervisory control facilities (e.g. FBM40 or FBM100) which use part of the VF band to transmit supervisory control signals.

The reliability of the radio relay systems, although very high, can be further enhanced using the protection switching facilities available. They are universally suitable for equipment switching (e.g. hot standby) or diversity operation and act on both the digital and the service channel transmission facilities.

In a (1 + 1) configuration (**Fig. 6**), the digital and service channel inputs on the transmit side each have an active splitter to connect them permanently in parallel. Equipment switching (hot standby) is shown in which an RF switch located in the channel branching filter arrangement applies one or the other transmit signal to the antenna. The switching command is furnished by a control unit which detects the "loss of transmit power" and "loss of oscillator stabilization lock" signals from the two transmitters.

Switching can also be initiated locally by hand or via a supervisory control facility.

On the receive side, the receive signal is fed to the two receivers via a 3-dB divider. The regenerated, HDB3-encoded baseband output signals from the two receivers are passed to a fast baseband switch which operates within a few nanoseconds. At the switch output, the particular baseband signal through-connected is made available to the standard interface (CCITT Recommendation G.703) in HDB3 code. The receive-side switching is controlled by signals from both receivers, such as "RF input level too low," "bit error rate too high," "AIS" or "loss of oscillator stabilization lock," after these have been linked with any commands entered by hand. All

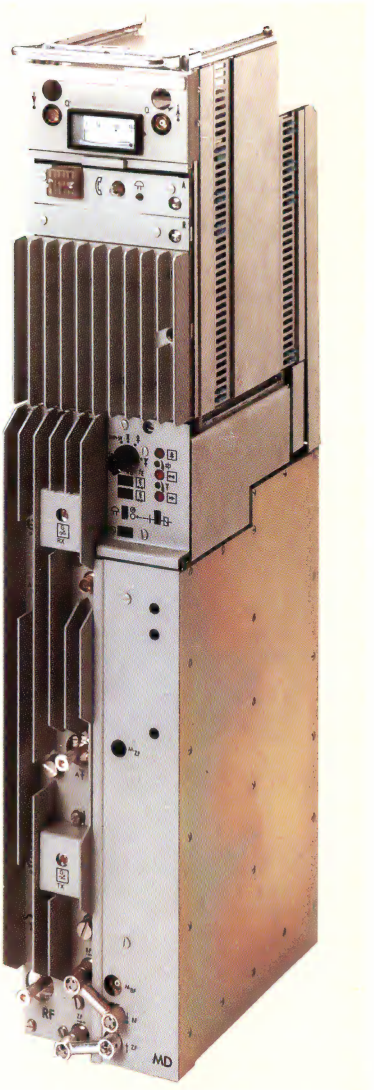


Fig. 7 Radio relay unit in style 7R

these signals can be applied to a supervisory control facility for transmission to a remote location. The protection switching unit is powered on a redundant basis from the power supplies of the two associated radio relay units.

Mechanical design

As is apparent from **Fig. 1** and **Fig. 7**, the mechanical design of the radio relay equipment reflects the strict concentration of all radio-frequency functions in one RF module and all capacity-related facilities in one modem module.

The vertical, style 7R units are 110 mm wide, 235 mm deep and 600 mm high. The upper, 110 mm wide section of the mounting system (**Fig. 7**) incorporates (from the top) the connectors and a meter, the service channel equipment (two plug-in modules) and the voltage converter. Below this are the compact,

54 mm wide RF and modem modules each of which forms an integral unit with the supervisory facility. The mechanical and, in particular, the electrical interfaces are designed so that any module of a group can be replaced readily without electrical adjustment. The electrical connections of the modules are provided as floating connectors on the rear panel and as coaxial connectors on the front panel (for baseband, IF and RF connections).

Station installation is straightforward and economical using either standard, style 7R racks, each of which accommodate three radio relay units, or prewired wall-mounting frames. There is space not only for the radio units but also the transmit and receive filters as well as the protection switching equipment. For mobile service, the DRS 2/800 radio relay unit can also be installed in a portable case.

Applications

The series of radio relay systems described for transmission of 2 or 8 Mbit/s in the frequency bands 800, 1800, 7200 and 7500 MHz is suitable for use at all public telecommunication network levels and in private transmission networks. Standard antennas (diameter between 2 and 3 m) in most applications provide a system margin of 40 to 50 dB, permitting hop lengths of 50 km and more when frequency diversity is employed. A particular attractive feature of these units is their extremely flexible design, covering a wide range of applications and enabling analog links to be converted to digital operation at very low cost.

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Digital Radio Relay Systems for Short- and Medium-Haul Networks

The systems currently preferred for use in short- and medium-haul networks transmit bit rates of between 2 and 34 Mbit/s. Since the hop lengths to be spanned are mainly between 10 and 30 km, these systems can be operated in the 13-GHz and 15-GHz bands where hop lengths of this order are still achievable with the availability required despite high rain attenuation.

Altogether, three systems have been developed for this network level. Two of them operate in the 15-GHz band at bit rates of 2×8 (2×2) Mbit/s and 34 Mbit/s, respectively; the third, operating at a bit rate of 34 Mbit/s, is intended for the 13-GHz band. All three systems employ quaternary phase-shift keying (QPSK) with direct modulation of the radio frequency (RF) carrier on the transmit side and coherent demodulation on the receive side. After briefly discussing RF channel arrangements and available transmission capacities, the authors describe the electrical and mechanical design of these systems and provide notes on their use. System data and test results are also given.

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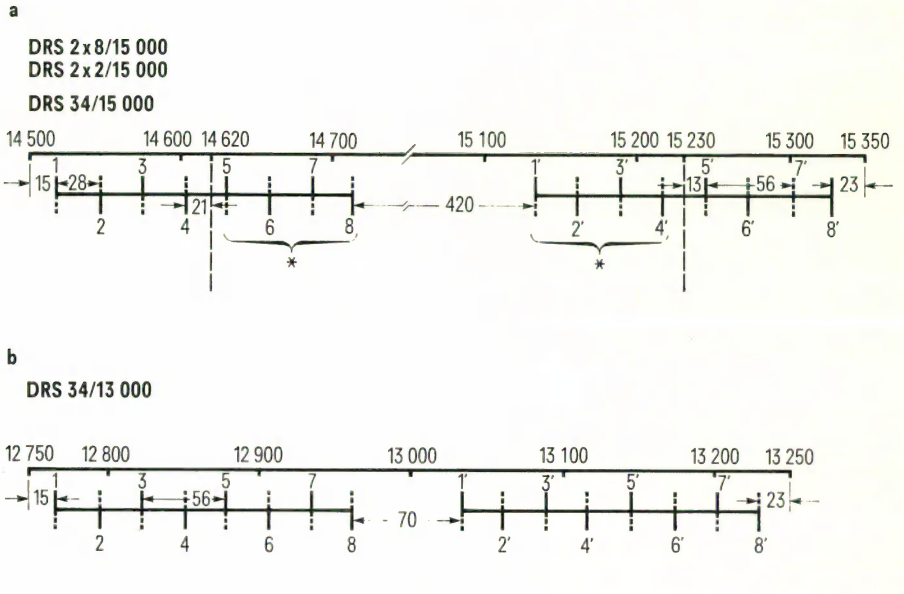
The hop lengths to be spanned on medium- and short-haul routes are mainly between 10 and 30 km, i.e. considerably shorter than the basic hop length of some 50 km specified by the CCIR for long-haul networks. It is thus possible at this network level to use systems in the 13-GHz and 15-GHz bands. The equipments developed for this application employ QPSK and OQPSK (offset quaternary phase-shift keying) with direct modulation of the RF carrier in the transmitter. They therefore differ fundamentally from the 34-Mbit/s systems for the long-haul network which employ OQPSK with indirect modulation [1] and also from the local network systems in the 18.7 and 22-GHz bands operated at up to 34 Mbit/s with 4FSK (frequency-shift keying) [2]. These equipments therefore form a distinct group of systems whose features and characteristics will now be described.

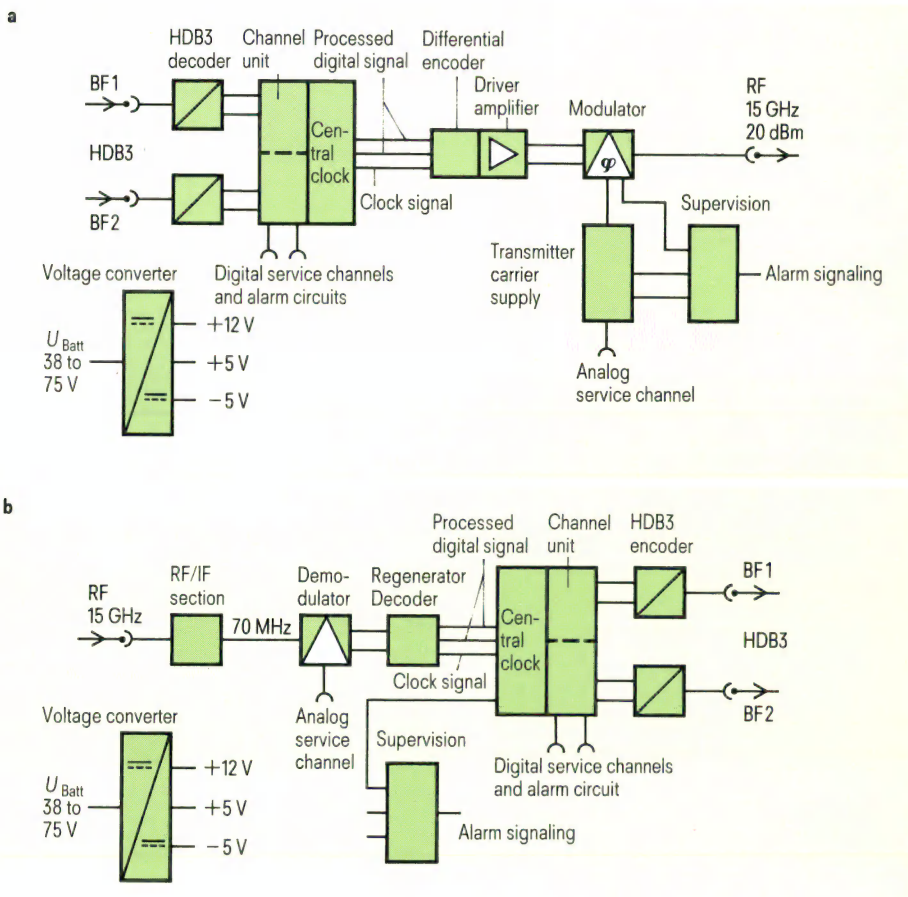
RF channel arrangement and transmission capacity

Fig. 1a shows the channel arrangement specified in CCIR Recommendation 497, Report 607 (or Note 10) for the two 15-GHz systems, DRS 2×8 (2×2)/15000 and DRS 34/15000. This arrangement provides for a total of eight channels in each of the upper and lower halves of the band for transmitting 2×2, 2×8 or 34 Mbit/s. In all cases the spacing between adjacent channels using the same polarization is 28 MHz. With orthogonal polarization, it is possible to reuse the same channels on the same route (cochannel operation); it is also possible (e.g. at nodal points) to employ a channel arrangement displaced by 14 MHz. If required, 2×2, 2×8 and 34-Mbit/s signals can be transmitted together over a route via a single



* Expansion if required

Fig. 1 RF channel arrangement for medium-haul systems (frequencies in MHz)
a RF channel arrangement in 15-GHz band per CCIR Recommendation AB/9
b RF channel arrangement in 13-GHz band per CCIR Recommendation 497



BF Baseband frequency
φ Phase
HDB3 HDB3 code (high density bipolar of order 3)
IF Intermediate frequency
RF Radio frequency

Fig. 2 Functional diagram of DRS 2×8 (2×2)/15000 digital radio relay systems
a Transmitter
b Receiver

antenna, the signals being combined at channel branching filter level. When the 15-GHz channel arrangement is fully utilized with 34-Mbit/s systems in cochannel operation, it provides a maximum transmission capacity of $2 \times 8 \times 480 = 7680$ voice circuits. However, as **Fig. 1a** shows, West Germany's PTT, the Deutsche Bundespost is currently using only half the 15-GHz band – i.e. from 14.5 to 14.62 GHz and 15.23 to 15.35 GHz with 2×4 RF channels in each of the upper and lower halves of the band, thus reducing the transmission capacity to 3840 voice circuits.

Fig. 1b shows the RF channel arrangement for the 13-GHz system in accordance with CCIR Recommendation 497. This provides for eight RF channels each spaced 28 MHz apart in the lower and upper halves of the band; the spacing of the adjacent channels using the same polarization on one antenna is 56 MHz. Employing cochannel operation, which is likewise available with this system, the band capacity is again $2 \times 8 \times 480 = 7680$ voice circuits.

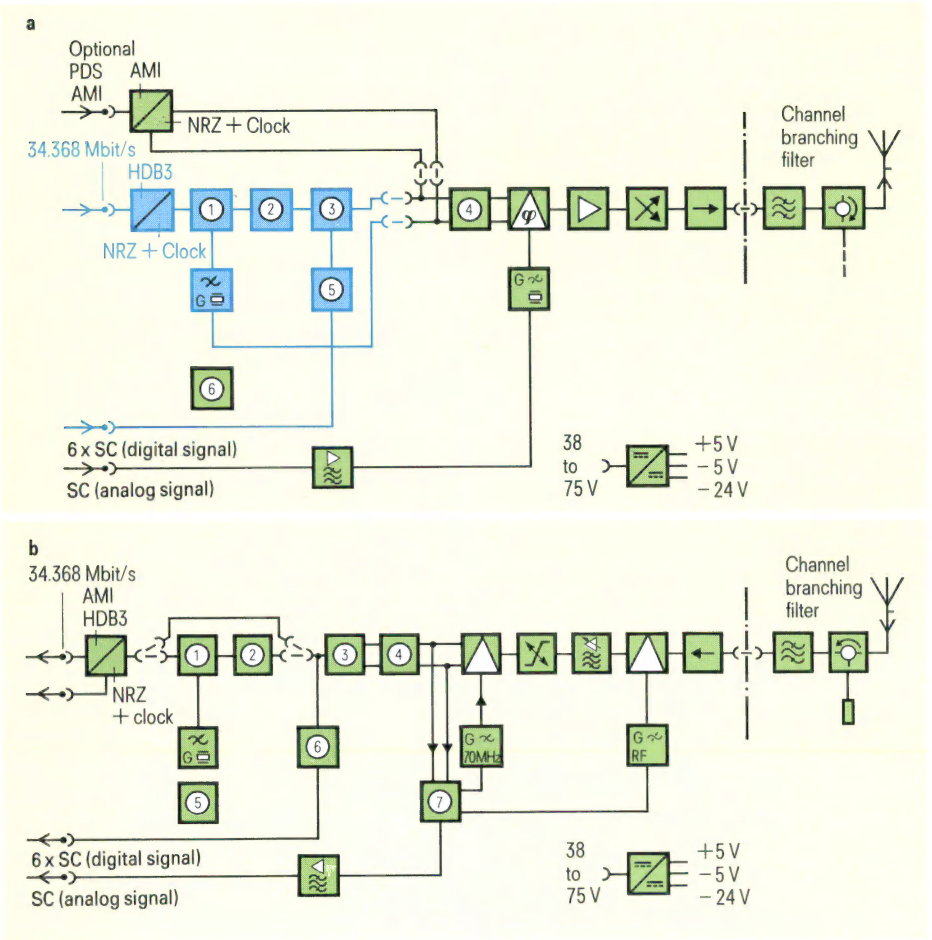
Electrical design

DRS 2×8 (2×2)/15000

This system can transmit two mutually independent, plesiochronous (same nominal clock frequency) bit streams of either 8 or 2 Mbit/s. The equipment can be set to the desired bit rate by means of U-connectors. **Fig. 2** shows the electrical design of transmitter and receiver.

Transmitter

In the baseband section of the transmitter (**Fig. 2a**), the two incoming plesiochronous digital signals are first fed to the *HDB3 decoders* (HDB3 high density bipolar of order 3) where the signals are amplified and equalized. Cable losses of up to 12 dB (at the frequency of half the bit rate) can be compensated. The timing is then recovered and the signals are regenerated and converted to non-return-to-zero (NRZ) format with the associated timing. If no HDB3 input signals is present, a maintenance alarm is transmitted to the supervision module and an alarm indication signal (AIS; all ones) is injected. If only one baseband signal is employed, the other (unused) channel is automatically loaded with AIS.



①	Elastic store	HDB3	HDB3 code (high density bipolar of order 3)
②	Scrambler	NRZ	Nonreturn-to-zero
③	Bit insertion	PDS	Processed digital signal
④	Differential encoder	SC	Service channel
⑤	Frame generation	①	Elastic store
⑥	Supervision	②	Descrambler
——	For repeater operation	③	Differential decoder
——	For terminal operation	④	Regenerator
AMI	AMI code (alternate mark inversion)	⑤	Supervision
φ	Phase	⑥	Frame supervision
G	Generator	⑦	Synchronization

Fig. 3 Functional diagram of DRS 34/13000 and DRS 34/15000 digital radio relay systems

a Transmitter
b Receiver

In the *channel unit with central clock*, the two plesiochronous bit streams present in NRZ format are first converted to an identical higher clock frequency of 8.64 (2.144) MHz for both channels. This is effected in a justification circuit in which the signals are each provided with a system multiframe.

The multiframe contains not only the frame alignment signal but also added bits for RF channel identification and for three 16 or 32-kbit/s digital service channels, as well as a justifying digit. The processed signals (NRZ with 8.64 or 2.144-MHz clock) are then scrambled and fed to a *differential encoder with driver amplifier* in which the control voltages for driving the four-phase modulator in the transmitter RF section are generated.

The transmitter RF section, comprising the *transmitter carrier supply* and the *modulator*, is of identical design for all the 13 and 15-GHz medium-haul systems. In the transmitter carrier supply, the RF carrier to be modulated is generated by a varactor-tuned Gunn oscillator and locked to the crystal-controlled reference frequency of a 120-MHz oscillator via two phase-locked loops (PLL). The principle is similar to that used in other systems. The crystal frequency is suitable multiplied and mixed with the RF frequency, the resulting difference frequency being used to correct the RF frequency.

The frequency can be changed simply by changing the 120-MHz crystal in the crystal-controlled reference oscillator to one of the eight RF channels. Frequency modulation of the 120-MHz crystal-controlled oscillator also provides an analog service channel.

The output frequency of the Gunn oscillator is fed directly to the two-stage, four-phase modulator which produces the QPSK-modulated RF signal. At the transmitter output, a supervision circuit ensures that if the transmit power drops by more than 4 dB or lock is lost in either of the PLLs, a maintenance alarm is produced. In the latter case the transmit power is shut down in order to prevent any unwanted emissions.

Receiver

Fig. 2b shows the functional diagram of the receiver. As with the transmitter, the receiver *RF section* is of identical design for all the medium-haul systems in the 13 and 15-GHz bands. The received RF signal from the channel branching filter is down-converted to the 70-MHz IF and amplified. The microwave power required for the conversion is supplied by a varactor-tuned Gunn oscillator which is controlled in frequency by an automatic frequency control (AFC) voltage derived from the demodulator. This allows an intermediate frequency (IF) of 70 MHz to be maintained with great precision. The signal is then bandlimited in an IF filter, amplified to a constant level in the main IF amplifier and fed to the demodulator.

In the *demodulator*, the IF signal is coherently demodulated to provide the two digital signals at the raised system clock frequency of 8.86 (2.144) MHz at the output. In addition, the AFC signal and the demodulated analog service channel signal are extracted from the control voltage loop of the reference carrier oscillator (Costas loop). Coherent demodulation of the two bit streams is followed by carrier recovery, *regeneration* and *decoding*. From the decoder, the two digital signals are fed to the digital signal processing section.

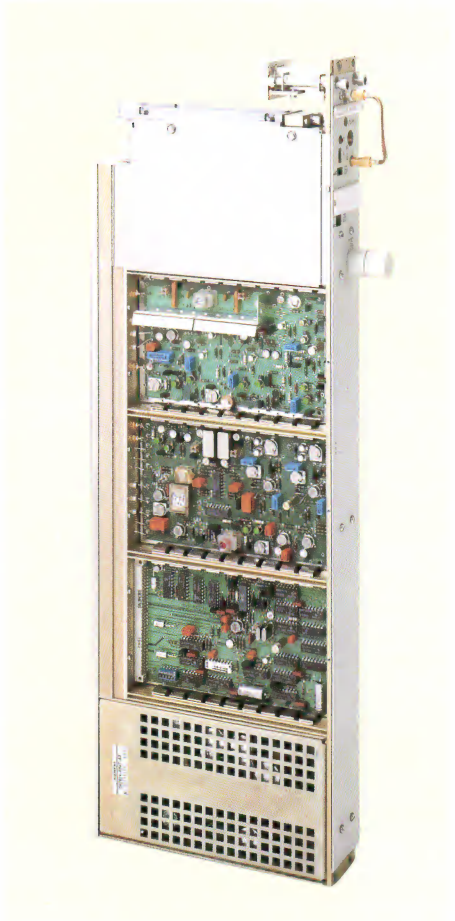


Fig. 4 Mechanical design of DRS 2×8 (2×2)/15000 digital radio relay system (style 7R6 receiver inset)

In the *central clock/channel unit,* the differentially decoded bit streams are first descrambled, the radio relay system frame is removed and the bits added for RF channel identification and for the digital service channels are extracted. Clock alignment circuits (dejustification) then restore the two plesiochronous bit streams to their original clock frequencies. The two NRZ signals are then converted in the *HDB3 encoder* to the ternary RZ signals in HDB3 code for the output interface.

The transmission quality is monitored in the receiver by checking the frame alignment signal for bit errors. If a bit error rate of 10^{-3} is exceeded or the RF channel identification received is not correct, the receiver initiates a service alarm. If transmission is disturbed, the receiver additionally inserts an AIS.

DRS 34/13000 and DRS 34/15000

As the functional diagram in **Fig. 3** shows, the electrical design of the 13-GHz and 15-GHz systems is virtually identical. Both systems employ the new 34-Mbit/s OPQSK modem which is described in detail in [1]. Unlike long-haul practice, the modem used at 15 GHz in the medium-haul network is a version with ordinary QPSK.

As systems such as the DRS 2×8 (2×2)/15000 described above employ direct modulation of the RF carrier, it is possible to dispense with the IF modulator described in [1] on the *transmit side* (**Fig. 3a**). In this case, the processed digital signal is fed as a control signal via the differential encoder directly to the two-stage, four-phase modulator mentioned earlier. In both of the 34-Mbit/s systems, the RF carrier is generated in the same way as in the DRS 2×8 (2×2)/15000 system. However, unlike these systems, the transmit power level is raised to 500 mW by a multistage transmit amplifier equipped with GaAs FETs.

On the *receive side* (**Fig. 3b**), the electrical design through to the main IF amplifier is identical to that of the DRS 2×8 (2×2)/15000 system. However, the 34-Mbit/s systems are additionally provided with an amplitude and delay equalizer. The demodulator and digital signal processing section are of identical design in every respect, including alarm signaling, to that of the 34-Mbit/s modem described in [1].

The system *power supplies* uniformly operate from the 60-V station battery and provide dc isolation in converting it to the supply voltages required for operation. A diagnostic plug permits connection of a built-in test meter to indicate operating voltages and levels.

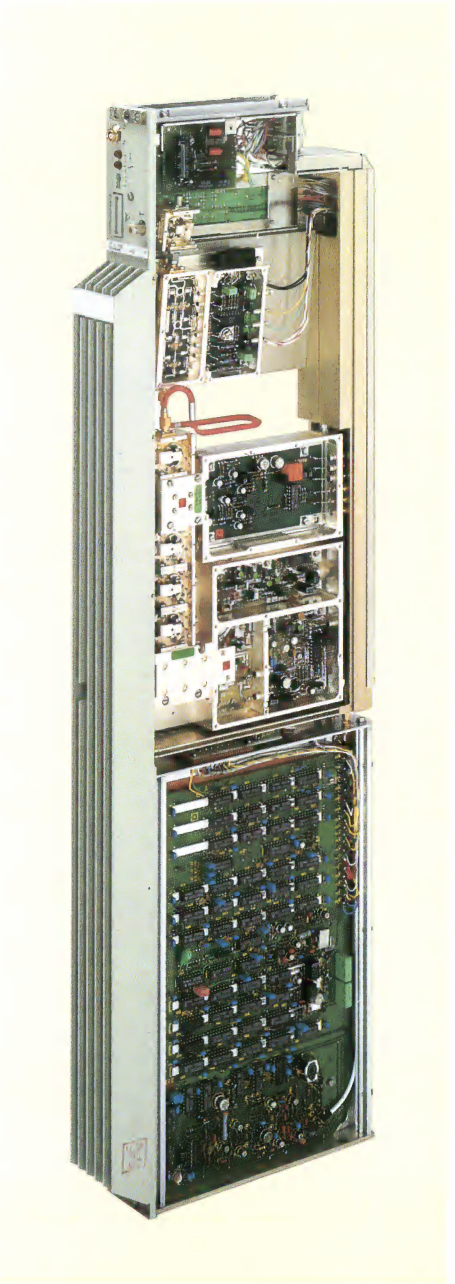


Fig. 6 Mechanical design of DRS 34/13000 digital radio relay system (style 7R6 transmitter inset)

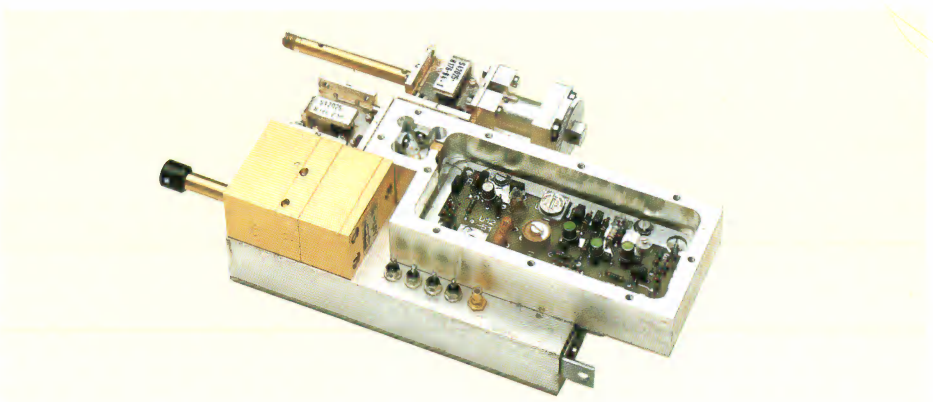


Fig. 5 Radio-frequency (RF) head of the DRS 2×8 (2×2)/15000 receiver

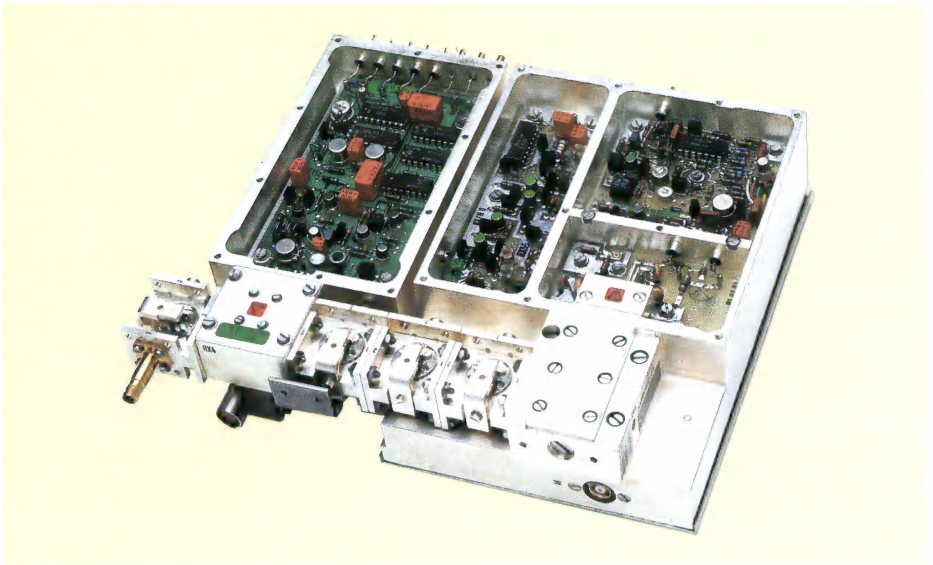


Fig. 7 Radio frequency (RF) head of DRS 34/13000 transmitter

Mechanical design

DRS 2×8 (2×2)/15000

In this system, the transmitter and receiver are designed as style 7R6 narrow insets 54 mm wide and 600 mm high. As shown in **Fig. 4** (receiver), the microwave components are always mounted in the upper part of the inset. The components form compact assemblies known as RF heads (**Fig. 5**), each containing the Gunn oscillator with carrier stabilization circuit, the RF phase modulator for the transmitter and the down-converter for the receiver. The central section contains the IF and baseband components and the digital signal processing circuit. The lower part of each inset accommodates the power supply as a separate module.

Up to three transmitters and three receivers including the associated channel branching filters can be accommodated in a narrow rack 2600 mm high. An adjacent empty rack is required for the waveguide run up to the antenna feeder connection.

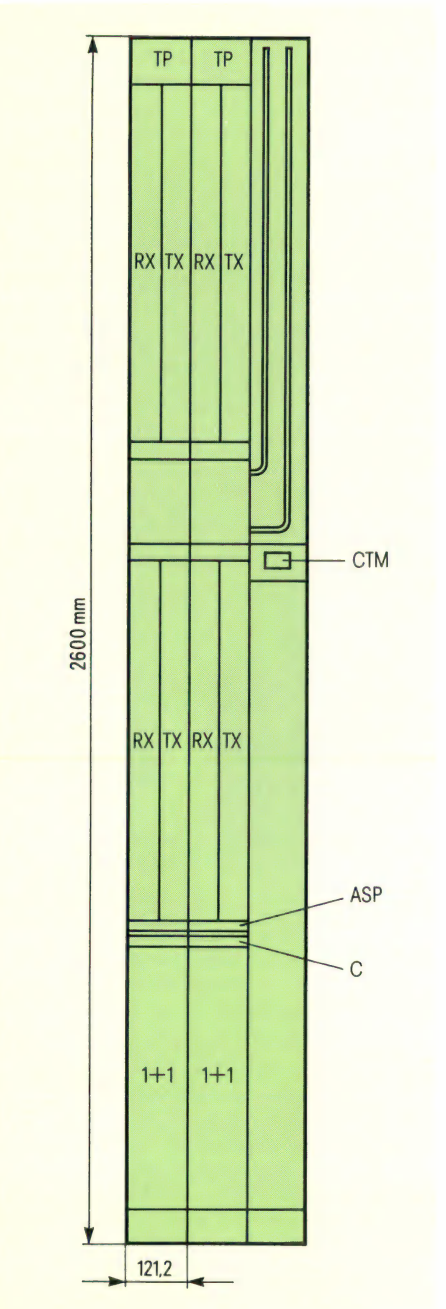
As this system is frequently used in network spurs where a dedicated radio relay infrastructure (e.g. telecommunication tower) may not be available, the equipment can also be installed in wall-mounted frames or accommodated in weatherproof cases with integral or remote antenna. This approach is particularly cost-effective in cases where long waveguide antenna feeders would otherwise be required. Up to two transmitters and two receivers can be accommodated in a weatherproof case. To allow for installation in weatherproof cases, the equipment is designed to operate at ambient temperatures of between −25 and +40 °C and requires neither heating nor cooling. The weatherproof case measures 740 mm × 760 mm × 600 mm (W × H × D).

The antennas used are parabolic reflectors 0.6 or 1.2 m in diameter with radome, whether located remotely or integral with the weatherproof case.

DRS 34/13000 and DRS 34/15000

In both of these systems the transmitters and receivers are designed as style 7R6 insets, each 800 mm high. **Fig. 6** shows the right-hand interior of the 13-GHz transmitter. The RF transmit amplifier is visible in the upper part of the equipment inset below the supervision circuit; below this is the transmitter RF head, an enlarged view of which is shown in **Fig. 7**. The lower section cointains the digital signal processing section and the power supply.

Two transmitters and two receivers including the associated channel branching filters can be accommodated in a narrow rack 2600 mm high. If the requirements are exacting, the availability can be increased with the aid of DESG 34 (1+1) or DESG 34 (N+1) digital protection switching equipment using line switching, space diversity or frequency diversity [3]. As the typical configuration for space diversity and transmitter protection in **Fig. 8** shows, an arrangement of this kind with four transmitters and four receivers including protection switching equipment, terminal panels and antenna feeders can be accommodated in three style 7R narrow racks.



ASP Alarm signal panel
C Two card compartments (for operating instructions)
CTM Central test meter
RX Receiver
TP Terminal panel
TX Transmitter

Fig. 8 Typical configuration for space diversity operation with (1+1) transmitter protection on DRS 34/13000 digital radio relay system

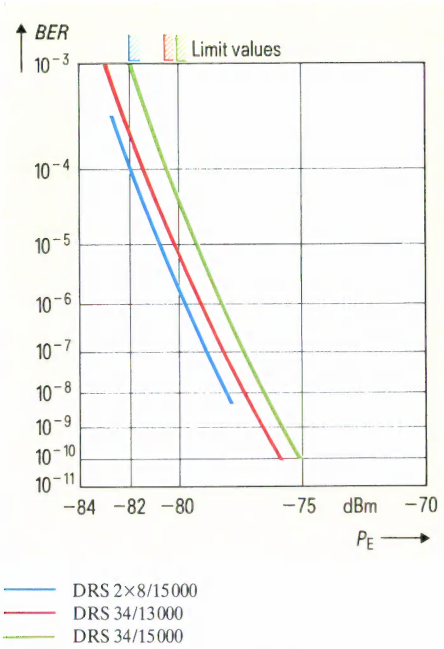


Fig. 9 Measured bit error ratio, *BER*, as a function of the receive level P_E in digital radio relay systems

Summary and prospects

The **table** lists the main specifications of the three systems for medium- and short-haul networks. In addition, **Fig. 9** shows the measured bit error ratio as a function of the receive level for the DRS 2×8 (2×2)/15000 and DRS 34/13000 systems. This shows that a sufficient margin is achieved with respect to the specified limit values.

The DRS 2×8 (2×2)/15000, DRS 34/13000 and DRS 34/15000 are three radio relay systems ideally suited to present-day requirements in medium- and short-haul networks, allowing even complex network structures to be implemented. However, it is anticipated that in future the traffic volume in medium-haul networks will rise considerably and that medium-haul systems will be used increasing to solve frequency coordination problems in long-haul network spurs. Both of these trends indicate that the medium-haul network will also require systems with much higher transmission capacities in the future.

Digital radio relay systems		DRS 2×8(2×2)/15000	DRS 34/13000	DRS 34/15000
Frequency bands	GHz	14.5 to 15.35	12.75 to 13.25	14.5 to 15.35
RF channel arrangement per CCIR		Rec. AB/9	Rec. 497	Rec. AB/9
Minimum channel spacing	MHz			
at a channel branching filter		28	56	28
for copolarization		28	28	28
for cross-polarization		0 or 14	0 or 14	0 or 14
No. of channel pairs		16	16	16
Bit rate	Mbit/s	2×8.448 (2×2.048)	34.368	34.368
No. of voice circuits per RF channel		2×120 (2×30)	480	480
Bandwidth of analog service channel	kHz	0.3 to 3.4	0.3 to 3.4	—
No. of digital service channels		3	6	7
Bit rate of a digital service channel	kbit/s	16.615 (8.375)	32	32
Type of modulation		QPSK	OQPSK	OQPSK
Transmit power	mW	100	500	500
Receiver noise figure	dB	≤ 9	≤ 7	≤ 8.5 (≤ 6.5 with RF pre-amplifier)
Receive level control range	dBm	−35 to −82	−30 to −81	−35 to −82
Receive level for $BER = 1 \times 10^{-3}$	dBm	< −82	< −80.5	< −80 (< −82)
System gain	dB	102	107.5	107 (109)
Spectrum efficiency	$\frac{\text{bit/s}}{\text{Hz}}$	1.2 (0.3)	2.5	2.5

BER Bit error ratio
OQPSK Offset quaternary phase-shift keying
QPSK Quaternary phase-shift keying
RF Radio frequency

Table Main specifications of digital radio relay systems for short-haul and medium-haul networks

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Rudolf Fischer, Peter Kloeber, Uwe Lehmann and Hans-Jörg Thaler

Digital Radio Relay Systems for Local Networks

Exploitation of the frequency bands above 11 GHz is a particular challenge for radio relay engineering, as higher frequencies are subject to a considerable additonal propagation loss due to precipitation. Consequently, the achievable hop lengths generally decrease sharply with increasing frequency but are determined individually by the frequency distributions of the precipitation intensities, the permissible unavailability of the link and the design of the radio relay system to be used. In the 18-GHz band, which is attractive for a wide variety of radio relay applications by virtue of its large bandwidth, it becomes impossible, for example, to implement long-haul links with hop lengths of around 50 km; the distances which can be spanned in practice are between 5 and 20 km. The preferred area of application for 18-GHz radio relay systems is therefore at the lower network levels, particularly in conurbations where short hops predominate. These applications impose on radio relay systems in the 18-GHz band special requirments in terms of design flexibility, cost-effectiveness and infrastructure provision.

In this article, a general discussion of the relationship between rain attenuation and availability is followed by a description of a flexible radio relay system, the DRS 2-8-34/18700, which provides particularly attractive design features and transmission capacities of 2, 8 or 34 Mbit/s. After describing the electrical functions and system design, the authors provide application notes for this family of systems.

Rain attenuation and availability

The additional attenuation of electromagnetic waves due to precipitation particles (raindrops) increases markedly with frequency when the wavelength approaches the order of magnitude of the particle dimensions. Unlike *free-space attenuation* which increases by around 6 dB each time the distance doubles, the *precipitation attenuation* in dB (for a given precipitation intensity) is directly proportional to the distance. This relationship is apparent from **Fig. 1** which shows, as a function of the path length, the attenuation values which are exceeded due to rain in the stated percentages of time (yearly average) at 18.7 GHz on the less favorable horizontal polarization. The rain climatic zones used (per CCIR Report 563) are each characterized by the rain intensity which is exceeded for 0.01% of the time. On longer hops, the additional attenuation ceases to be exactly proportional to the length owing to the limited size of the rain cells, so that the increase in the additional loss with distance is somewhat lower (and therefore more favorable).

If the additional loss due to rain exceeds the specified fading margin for a particular hop, the link fails. Rainfall generally lasts for longer than 10 s; consequently, outages caused by rain attenuation are the main factor contributing to the unavailability of a link. Unlike long-haul links (high-grade), there are as yet no binding CCIR recommendations concerning the availability of medium- or local-grade short-haul links in the lower network levels [1]. As a provisional design objective, the Deutsche Bundespost permits an unavailability per hop of 0.005%.

If the distance-related fading margin is additionally plotted on **Fig. 1,** the point of intersection with the corresponding rain attenuation curves gives the hop length that can be spanned. For system design purposes (with a reference fading margin of 50 dB for a 1 km hop), the resultant hop lengths for the central European climatic zones and a permissible unavailability of 0.005% are 9.2 or 19.9 km. **Fig. 1** also shows the considerable effect of the permissible unavailability on the achievable range. Moreover, it is clear from **Fig. 1** that, given low unavailabilities, the system margin (based mainly on equipment data and antenna gain) has relatively little effect on the range. This is a consequence of the already very high attenuation per kilometer in the small percentages of time under consideration (10 dB/km for 0.0005% of the time and rain zone K). It is only if the permissible unavailabilities are very high (e.g. 0.1%) that an appreciable improvement in the range is obtained through an increased system margin (e.g. as the result of a higher transmitter output power). These relationships which similarly apply to all the frequency bands above 11 GHz clearly indicate that the achievable hop lengths for economical system application are primarily determined by the permissible unavailability, i.e. by a design objec-

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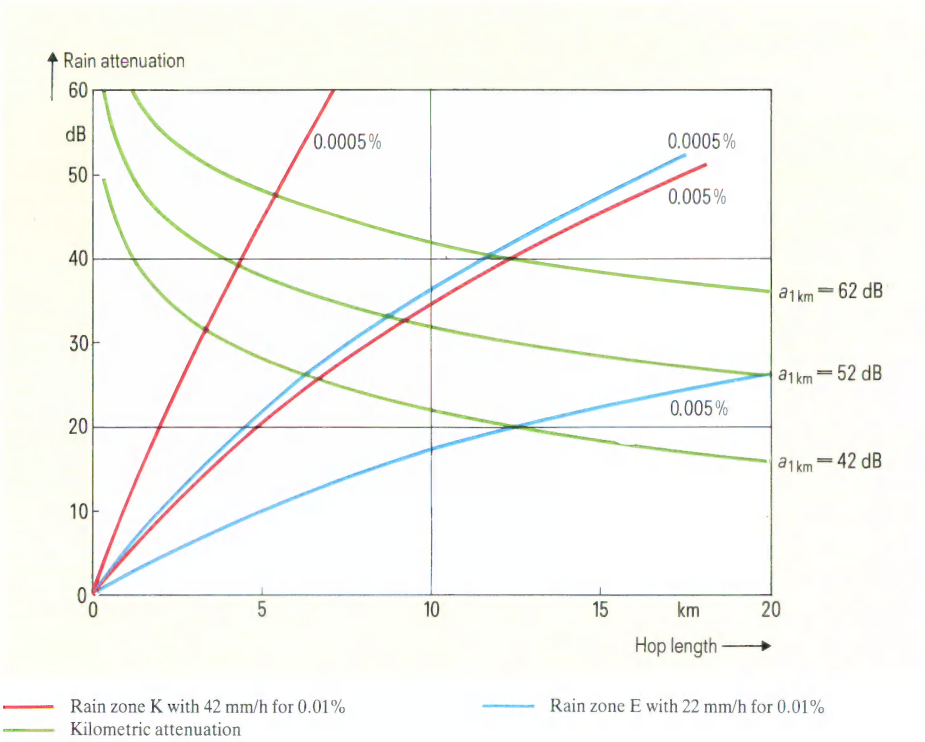


Fig. 1 Ranges in the 18-GHz band for different unavailabilities, system margins α_{1km} and rain zones

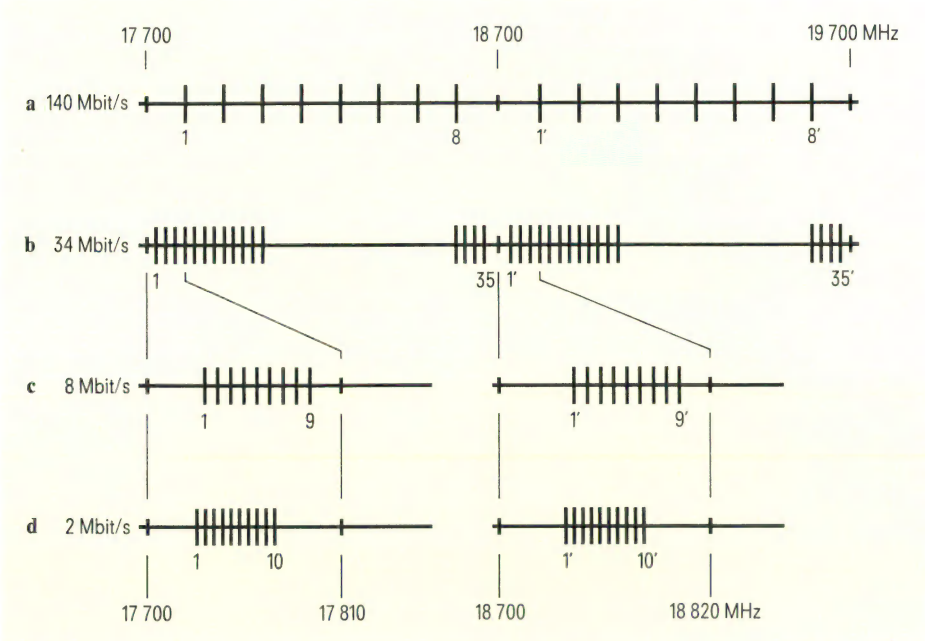


Fig. 2 RF channel arrangement in the 18-GHz band per CCIR Recommendation 595

a 140 Mbit/s
b 34 Mbit/s
c 8 Mbit/s
d 2 Mbit/s

tive. Freedom to specify the system and equipment parameters is controlled by the technical and technological possibilities and is comparatively limited. The system development objective was therefore to exploit all technical and technological possibilities in order to obtain the optimum system characteristics and a particularly cost-effective system design.

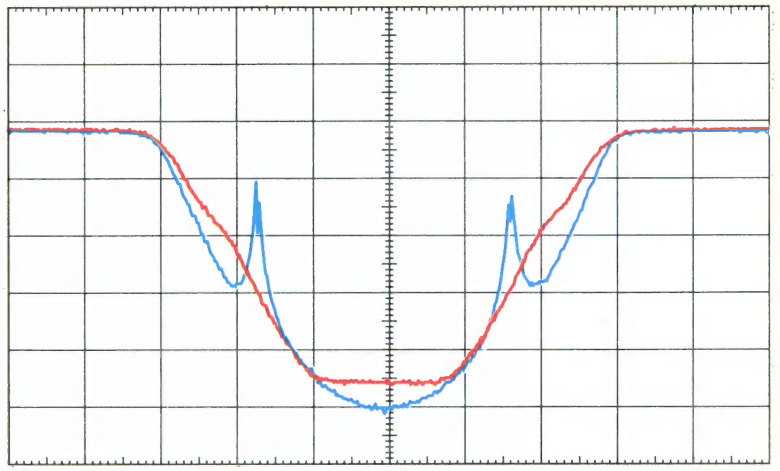
RF channel arrangement

For the 2 GHz wide frequency band 17.7 GHz to 19.7 GHz, the CCIR Recommendation 595 specifies various channel arrangements oriented to the 34- and 140-Mbit/s bit rates laid down by the CCITT and the spectrum utilization possible in lower frequency bands with classical modulation schemes such as QPSK (phase-shift keying) (**Fig. 2**). Channel spacing of 110 MHz with eight radio-frequency (RF) channel pairs is recommended for transmission of 140 Mbit/s. Further division by a factor of 4 produces a 27.5 MHz spacing, providing a total of 35 RF pairs for transmitting 34 Mbit/s. This produces spacings very similar to those in the 13- and 15-GHz bands (28 MHz for 34 Mbit/s with 4PSK) [2]. Channel arrangements for lower-capacity systems (2 and 8 Mbit/s) are allowed by the CCIR to be individually adopted by the administrations through the use of further subdivisions. Taking into account the "spectrum efficiency" and "frequency stability" aspects, spacings of between 7 and 15 MHz and between 2.5 and 5.5 MHz are recommended for 8 Mbit/s and 2 Mbit/s, respectively. **Fig. 2** shows the subdivision selected with 7.5- and 5-MHz spacings.

The RF channel arrangements specified in CCIR Recommendation 595 are unsuitable for the North American transmission hierarchy. In consideration of the extremely diverse usage of the 18-GHz band, the US Federal Communications Commission (FCC) has adopted different band divisions and arrangements [3]. The specified spectrum efficiency of at least 1 bit/s/Hz imposes on system design similar requirements to those laid down by the CCIR.

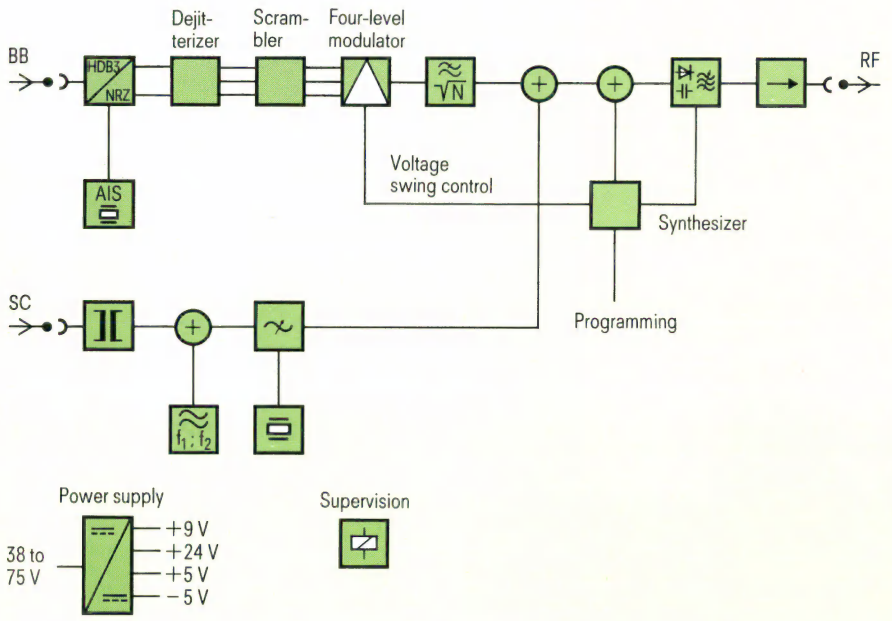
Modulation schemes and system design

Transmitter designs providing direct modulation in the RF band have proved particularly attractive in terms of cost and efficiency, especially at higher frequencies, and are therefore preferred [2, 4]. The spectrum limiting required for phase-shift keying (e.g. QPSK) with RF modulators (in order to prevent adjacent channel interference) can be achieved on medium- and high-capacity systems by using suitably dimensioned RF or channel branching filters, though at the cost of added complexity and attenuation. For lower-capacity systems (e.g. 2 and 8 Mbit/s), the limiting of a PSK spectrum (in the case of direct modulation in the 18-GHz band) would require RF filters with frequency stability of an unattainable order and with considerable attenuation. Consequently,



4FSK QPSK

Fig. 3 Spectra for 34-Mbit/s systems with 4FSK (frequency-shift keying) without RF (radio frequency) filtering and QPSK (quaternary phase-shift keying) with RF filtering (vertical scale: 10 dB per division) horizontal scale: frequency 10 MHz per division, center frequency 17.975 GHz)



AIS	Alarm indication signal	NRZ	NRZ code (nonreturn-to-zero)
BB	Baseband	RF	Radio frequency
HDB3	HDB3 code (high density bipolar of order 3)	SC	Service channel
N	Division factor		

Fig. 4 Functional diagram of the transmitter of the DRS 34/18700 digital radio relay system

directly modulated QPSK with RF filtering has to be ruled out for bandwidth-efficient transmission of low and medium bit rates in the 18-GHz band. Possible alternatives are QPSK or 4QAM (quadrature amplitude modulation) with indirect modulation in the intermediate-frequency (IF) band and spectrum limiting by means of baseband or IF filters. The required up-conversion from the IF to the RF band involves a considerable conversion loss and must be largely linear, as must the subsequent RF amplification that is generally required. As a result, a QPSK transmitter with indirect modulation is generally more costly than a directly modulated design and this cost can only be marginally reduced by using a single common carrier supply for transmitter and receiver.

A much more satisfactory method of producing a band-limited signal spectrum at low cost and reasonable efficiency has proved to be *direct frequency-shift keying* (FSK) of the RF oscillator. The nonlinear relationship between modulated signal or instantaneous frequency and RF spectrum allow compact RF spectra to be obtained even without baseband filtering. If baseband filters are used, it is possible, as shown in **Fig. 3,** for a carrier modulated with 4FSK at 34 Mbit/s to produce an RF signal whose RF spectrum is just as compact as that of a QPSK signal limited by a six-section filter. FSK also allows the modulation density and frequency shift to be selected to produce a signal with optimum spectral width and interference rejection.

In addition to simple signal generation and spectrum limiting, frequency-shift keying offers the further advantages of immunity to gain nonlinearities as well as the possibility of simple and robust incoherent demodulation using a frequency discriminator. This means that considerably less stringent demands are placed on the short-term stability of the oscillators than for PSK (or QAM) with coherent modulation. The slightly higher signal-to-noise ratio required for incoherent demodulation is compensated by the elimination of the modulator and its associated attenuation. For the same oscillator output in the transmitter, directly modulated PSK and 4FSK systems provide approximately the same system margin, but with clear practical advantages in favor of the FSK solution.

Further advantages of direct FSK modulation are that it is readily adaptable to burst operation as required on point-to-multipoint systems and allows analog modulation (e.g. for TV transmission) with only slight modification of the system design.

System design

In the view of the above mentioned advantages, the design adopted for the

digital radio relay system described in this article for transmitting 2, 8 or 34 Mbit/s in the 18-GHz band employs the 4FSK method with direct modulation of the RF oscillator on the transmit side and incoherent demodulation on the receive side. Since the transmitter and receiver are designed as self-contained units in order to provide maximum flexibility, it is possible to adapt to any RF channel arrangement irrespective of the transmit-receive separation. Each comprises an RF module, a baseband/IF module for a specific bit rate and the power supply. All the units are designed to operate in an ambient temperature of between −25 and +65 °C.

For use in the lower network levels it is generally necessary to provide single-channel links. Any expansion of capacity can be accommodated by converting to a higher-order bit rate or by using a second system operated with orthogonal polarization. There is as yet no provision for operating a route with different radio frequencies in parallel, so no channel branching facility is required. Channel selection in the double-conversion receiver is effected by relatively wideband channel group filters at RF and relatively narrowband filters at the first (high) IF (f = 790 MHz) and the second (final) IF (f = 70 MHz).

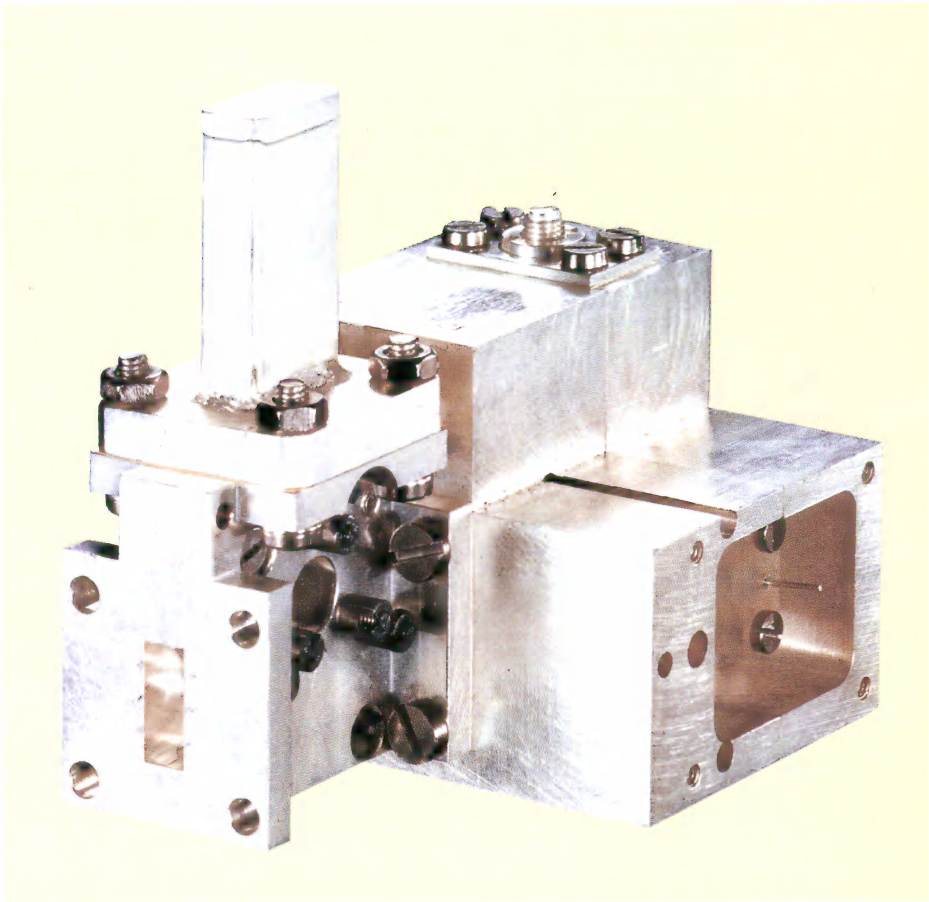


Fig. 5 RF oscillator for 18 GHz with waveguide isolator

Electrical design of the transmitter

Fig. 4 shows the functional diagram for the transmitter. The HDB3-encoded (HDB3 high density bipolar of order 3) baseband input signal is first equalized to compensate for frequency-dependent cable losses. It is then regenerated and split up into two parallel, binary NRZ (nonreturn-to-zero) signals at half the bit rate for further processing. The signals are passed through a dejitterizer, then a scrambler and finally converted to a baseband signal with four amplitude levels whose voltage swing can be controlled. After filtering in the transmit-side baseband filter, this signal is fed via an isolating amplifier to the modulation input of the RF oscillator. This results in four-level modulation of the radio frequency (QPSK).

The RF oscillator is a Gunn device with an output power of 100 mW (**Fig. 5**) and is electronically tunable over each subband covering more than 350 MHz (VCO voltage-controlled oscillator). A microprocessor-controlled synthesizer stabilizes the oscillator frequency, the transmit frequency being coded by soldering pins in a plug mounted outside the transmitter inset (e.g. in the inset housing). Frequency tuning is effected automatically, thereby obviating the need for adjustments when the unit is changed.

In order to provide frequency stability, the RF signal is converted via a harmonic mixer to an IF control signal. This signal is fed to a phase-locked loop (PLL) for frequency stabilization; it is also used for deriving a signal to control the voltage swing of the baseband signal so that the frequency shift and hence the width of the RF spectrum remains constant.

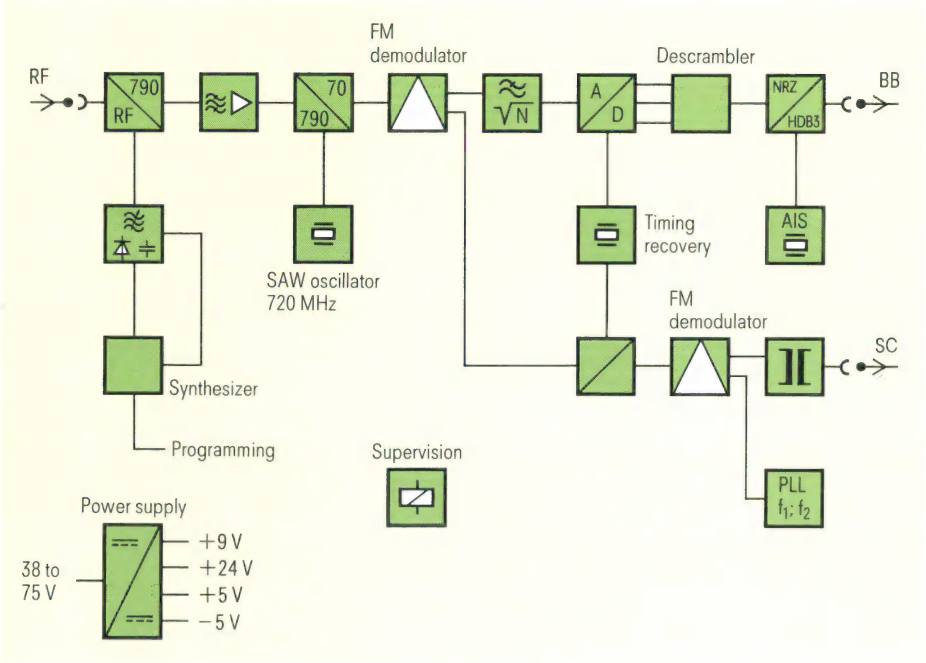
In the frequency range above the band-limited digital signal, a frequency-modulated auxiliary carrier is added to the baseband for transmission of an analog service channel and a marker tone for RF channel identification.

Transmitter supervision is by means of "equipment fault" and "loss of baseband" signals. These are indicated locally via an LED on the unit itself and can be extended to any available remote supervisory facility via a potential-free relay contact. If the baseband signal is absent, an AIS (alarm indication signal) is fed into the signal path. If the frequency stabilization circuit malfunctions, the RF output signal is suppressed to prevent emission of a spurious and possibly interference-producing RF signal.

Electrical design of the receiver

The functional diagram of the receiver is shown in **Fig. 6**. The RF signal from the antenna passes through an RF channel group filter and is converted by the receiver to the final intermediate frequency of 70 MHz in two stages. The adoption of double down-conversion provides effective selectivity in the first and second IF bands. This permits the use of relatively wideband, low-loss RF filters each of which is applicable to several RF channels.

The RF oscillator in the receiver differs from that in the transmitter only in hav-



A/D	Analog-digital converter	*N*	Division factor
AIS	Alarm indication signal	NRZ	NRZ code (nonreturn-to-zero)
BB	Baseband	PLL	Phase-locked loop
FM	Frequency modulation	RF	Radio frequency
HDB3	HDB3 code (high density bipolar of order 3)	SAW	Surface-acoustic-wave
		SC	Service channel

Fig. 6 Functional diagram for the receiver of the DRS 34/18700 digital radio relay system

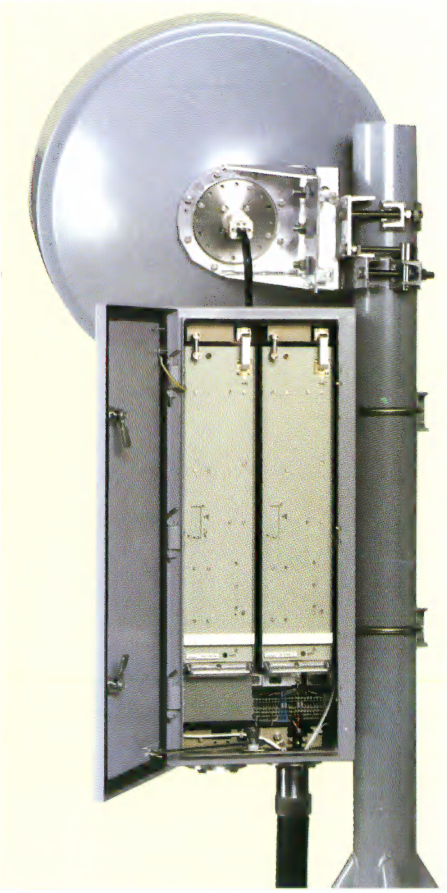


Fig. 7 Mechanical design of the weatherproof case with equipment insets and antenna

ing a lower output power and not requiring a modulation facility. Its frequency is likewise set via a coding plug mounted outside the inset (in the inset housing).

In the first IF band with a center frequency of 790 MHz the signal passes through a low-noise amplifier and a fixed-tuned channel filter used primarily for image-frequency rejection. The local oscillator signal required for the subsequent second conversion to the final intermediate frequency band (center frequency 70 MHz) is generated by a transistor oscillator whose frequency is stabilized by a surface-acoustic-wave resonator [5]. The IF signal subsequently passes through a band-pass filter for adjacent channel rejection and to limit the noise power. The signal is then raised in a limiting IF amplifier to a constant level independent of the RF input level. Finally, a frequency discriminator recovers the baseband signal which acquires its final pulse shaping in the following receive-end baseband filter. The transfer function of the entire signal path corresponds to a cosine roll-off characteristic (roll-off factor approximately 0.5) with negligible intersymbol interference overall.

Following timing recovery, the four-level, band-limited baseband signal is converted to two parallel binary signals in the regenerator; the scrambling effected at the transmit end is then reversed in the descrambler. Finally, the two data streams are combined and converted into an interface signal in HDB3 code.

The auxiliary carrier signal available at a secondary output of the demodulator is converted to a frequency of 450 kHz. After demodulation in a frequency discriminator, the analog service channel and channel identification tone are available for further detection.

In the receiver, the criteria for "incorrect or absent channel identification tone," "bit error ratio $\geq 10^{-3}$," (with the aid of a "pseudo-error detector") and "equipment fault" are monitored and combined to form one signal. This signal is indicated locally in the equipment inset or passed on to a remote supervisory facility via a potential-free relay contact. If the *BER* exceeds 10^{-3} or no marker tone is present, an AIS is additionally injected at the baseband output.

The transmitter and receiver each contain their own power supply which produces all the operating voltages required in the equipment insets from a primary supply of between 38 and 75 V.

Mechanical design of the units, weatherproof case and antenna

Transmitter and receiver are designed as style 7R2 insets measuring 200 mm × 110 mm × 500 mm and weighing some 9 kg each. The modules of the equipment insets – baseband section, RF section and power supply – are electrically linked by plug-in connectors and are easily replaceable. This enables the equipment to be easily adapted to suit different RF subbands and transmission capacities.

Since the DRS 2-8-34/18700 system is designed mainly for use in radio stations without PTT infrastructure, the units are mounted in a weatherproof case. The case can accommodate an equipment set (transmitter and receiver) with its associated connection and lightning-protection facilities and is designed primarily for fastening to supports 108 mm in

diameter (**Fig. 7**). Poles or brackets can therefore be used for easy mounting on the roofs or walls of buildings. The standard antenna used is a 0.6-m parabolic antenna with radome and can also be fixed to the 108 mm diameter system support. It is connected to the weatherproof case via a flexible waveguide (WR 42, E 100) to provide a simple and easily accessible system installation irrespective of the direction in which the antenna is pointed. The ease of installation and the compact size of the weatherproof case make the DRS 2-8-34/18700 system also ideal for the rapid deployment of temporary links.

If conditions allow, the equipment insets can also be accommodated remotely from the antenna (e.g. in a weatherproof case mounted inside the building, on the stairs or under the roof) or even in narrow racks or style 7R wall frames. Standard waveguides (E 190) are used for shorter antenna feeders, while it is recommended that an overmoded SIRAL® waveguide be used for longer connections [6].

The connecting cables from the weatherproof case (for baseband, power supply, alarm signaling and service channel) are routed to suit local requirements through a flexible or rigid metal conduit or via a special armored cable to a conveniently located junction box in the nearest available room of a building. In addition to the splitting facilities for the outgoing cables (for measuring and test purposes), it contains the lightning protection devices and the converter for providing the nominal dc voltage of 60 V from an ac source in cases where no station battery supply is available.

Frequency band	17,700 to 19,700 MHz		
Type of Modulation	4FSK, directly at RF		
Transmission capacities	2 Mbit/s	8 Mbit/s	34 Mbit/s
Frequency arrangement	5 MHZ	7.5 MHz	27.5 MHz
Adjacent channel spacing, same polarization	10 MHz	15 MHz	55 MHz
Transmitter output power	19 ± 2 dBm		
Noise figure	≤ 10 dB		
Transmit frequency stability	$\pm 20 \cdot 10^{-6}$		
Minimum receive level, for $BER = 1 \cdot 10^{-3}$	−84 dBm	−81 dBm	−75 dBm
System gain*	102 dB	99dB	93 dB
1-km fading margin	61 dB	58 dB	52 dB
RF interface	WR 42 waveguide		
Baseband interface	75 Ω coaxial (1.6 mm/5.6 mm) HDB3 code per CCITT Rec. G.703		
Antenna gain at 18.7 GHz*	≥38.9 dB		

* With 0.6-m antenna

BER Bit error ratio
HDB3 High density bipolar of order 3
FSK Frequency-shift keying
RF Radio frequency

Table Electrical specifications of the DRS 2-8-34/18700 digital radio relay system for various transmission capacities

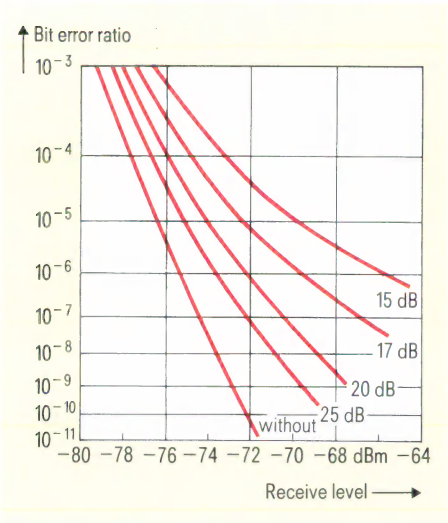


Fig. 8 System characteristic of the DRS 34/18700 digital radio relay system with and without cochannel interference (signal-to-cochannel interference ratio as parameter)

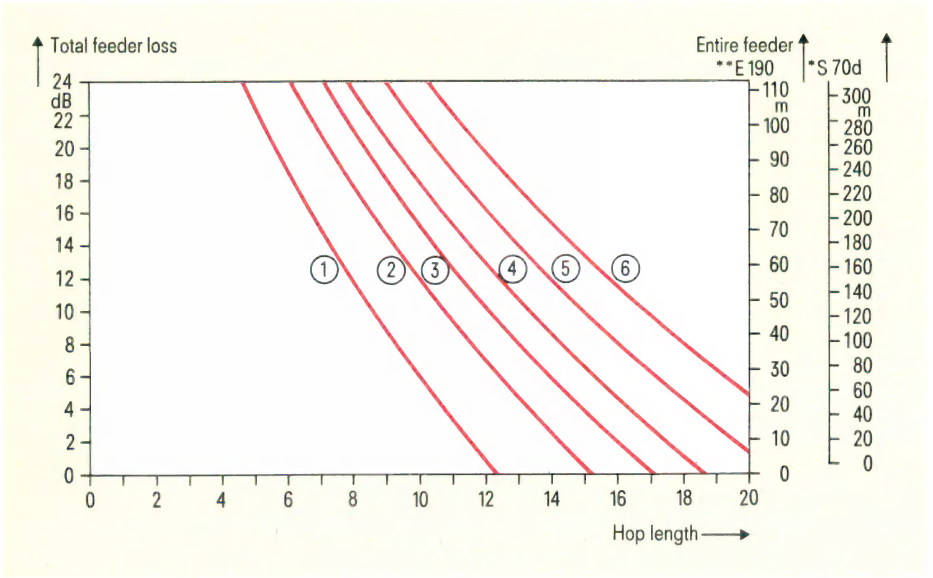
System data

The **table** summarizes the electrical specifications of the system for the various transmission capacities. Typical measured system characteristics (bit error ratio as a function of receive level) are shown in **Fig. 8** with and without cochannel interference. The **table** and the characteristics listed in **Fig. 8** demonstrate that the system data of the realized 4FSK system design are in practice comparable with those of a more costly 4PSK solution.

Applications engineering

The distances which can be spanned by using the DRS 2-8-34/18700 system are limited, as already explained, by the additional attenuation due to rain. **Fig. 9** is based on the rain climatic model for the central part of the Federal Republic of Germany (zone H per CCIR Report 721 with a rain intensity $R = 32$ mm/h for 0.01% of the year) and shows, for a permissible unavailability of 0.005% per hop [1], the achievable hop lengths as a function of the antenna feeder loss with various antenna sizes as parameters. For a given link length it is possible to obtain from this diagram the permissible feeder losses or the required antenna sizes. Using standard antennas (0.6 m diameter), hops of up to 12.4 km can be spanned in the most favorable case.

Links in the 18-GHz band can usually be planned with satisfactory results as if the cochannel and adjacent-channel interference were negligible due to the large number of radio frequencies available (up to 35 for 34-Mbit/s systems) and the good radiation patterns of the antennas. In the very rare cases where the capacity on a radio path can only be increased by using the same radio frequency on the orthogonal polarization, it will be necessary to allow for degradation – though slight – of the system characteristics in



* SIRAL® low-loss overmoded waveguide

** Eliptical waveguide

DRS 34/18700 digital radio relay system

Transmitter output power	$P_T = 19$ dBm
Received power	$P_R = -75$ dBm
Antennas and	0.6 m; 38.5 dB
antenna gains	1.2 m; 44.5 dB
	1.8 m; 48 dB
Branching filter losses	1 dB

Zone H (rain intensity for 0.01% of year 32 mm/h),
Outage = 0.005% per hop

① 0.6 m + 0.6 m
② 0.6 m + 1.2 m
③ 0.6 m + 1.8 m
④ 1.2 m + 1.2 m
⑤ 1.2 m + 1.8 m
⑥ 1.8 m + 1.8 m

Fig. 9 Permissible feeder losses for a given hop length using various antenna configurations

the event of precipitation reducing the cross-polarization discrimination.

When applying the system to urban areas, it is often impossible to obtain a direct line of sight between the transmitting and receiving stations at acceptable cost. In such cases, provided the distances are not excessive (allowing adequate system margins), an effective solution is to use passive repeater stations with plane passive reflectors or two parabolic antennas (back-to-back).

Summary and prospects

The DRS 2-8-34/18700 system presented here offers a flexible and economical means of rapidly setting up low-cost links in the lower hierarchy levels of telecommunication networks. In addition, it is particularly suitable for all kinds of special-purpose links (even for linking subscribers). The system design adopted is extremely easy to install and incorporates state-of-the-art technologies to provide low-maintenance operation with high reliability. It is thus an extremely cost-effective solution for a wide range of applications in a field which was previously almost exclusively the preserve of other transmission media.

Further extension of the range of applications is envisaged with additional system variants. Since the equipment is of modular design, there will be no problem in using new RF sections designed on the same principle to exploit the 23-GHZ band. This RF band with its higher rain attenuation will be reserved appropriately for the lower bit rates 2 and 8 Mbit/s. By combining RF sections with analog baseband or IF modules, it is possible to derive a TV transmission system (e.g. FM-TV/23000) suitable for both fixed and temporary applications (outside broadcast systems).

In addition, the system design described provides a particularly suitable basis for a point-to-multipoint system [7]. With systems of this kind, links are established via a single central base station to a comparatively large (and variable) number of outstations all using the same RF channel. Signals are transmitted to the outstations sequentially in TDM (time-division multiplex) with the base station serving all the outstations continuously via wide-area antennas (e.g. sector antennas). Transmission in the return direction, on the other hand, is demand-assigned in the TDMA mode (TDMA time division multiple access) with the outstations transmitting sequentially in their assigned time slots (burst mode).

The additional facilities required for TDM/TDMA operation are familiar items of satellite transmission technology [8]. The modules for baseband processing and sequence control can be easily combined with the point-to-point radio relay system described above, as the latter's modulation and demodulation process make it inherently suitable for burst-mode operation.

Point-to-multipoint systems offer attractive and cost-effective solutions unmatched by other transmission media, particularly in subscriber access systems and special purpose networks with a limited number of subscribers. It is anticipated that the use of such systems will play an important role in the future, resulting in a continuing increase in the spread of digital radio relay systems in the lower network levels.

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Digital Radio Relay Systems for the Transmission of 34-Mbit/s Signals

In the long-haul network, radio relay systems are usually operated in the frequency bands below 10 GHz in order to ensure reliability in spanning the hop length of some 50 km recommended by the CCIR. The modulation scheme employed by these systems for transmitting at 34 Mbit/s is generally OQPSK (offset quarternary phase-shift keying) with indirect modulation. The latter allows the signal at repeater stations to be through-connected at IF in special circumstances. By contrast, 34-Mbit/s systems for the medium-haul network employ direct modulation of the radio frequency (RF) carrier in the frequency bands above 10 GHz [1].

This article first discusses a new OQPSK modem in which baseband processing has been implemented using semi-custom, large-scale integrated circuits in CMOS standard cell technology (CMOS complementary metal oxide semiconductor). Two series of radio relay systems are then described. In the first, which is intended for the 2-GHz band, the transmitter and modulator are integrated in one equipment inset, the receiver and demodulator in another [2]. In the second series of systems, employed in the 6.4- to 8.5-GHz band, transmitter and receiver share a common equipment inset, with the modulator and demodulator forming separate equipment insets. The article concludes with system data and test results.

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For the transmission of 34-Mbit/s digital signals in the long-haul network, there are two equipment families available of essentially the same system design but differing mechanical design:

- *DRS 34/1900-2400-2600 system family* with one narrow inset for the transmitter and modulator and another for the receiver and demodulator (each 54 mm wide), and
- *DRS 34/6700-7500-8400 system family* with a 110 mm wide common inset for the transmitter and receiver and 54 mm wide insets for the modulator and demodulator.

Although of differing mechanical design, the two system families employ the same OQPSK modem with modulation and demodulation at the 70-MHz intermediate frequency (IF). This offers advantages in terms of reliably meeting the more stringent transmission quality requirements in long-haul networks and allows IF through-connection at repeater stations. In addition, with the equipment functions clearly separated by an IF interface on the modem side, it is possible to provide optimum filtering of the transmit and receive spectra.

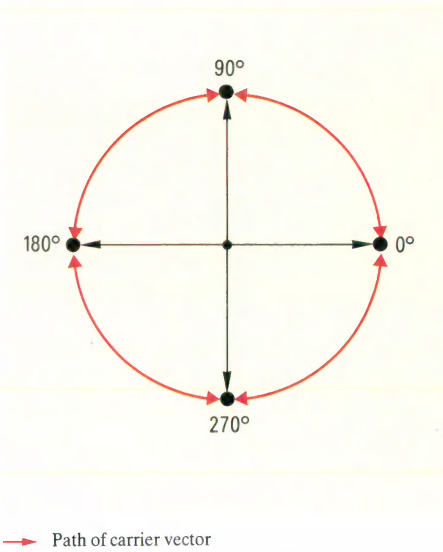
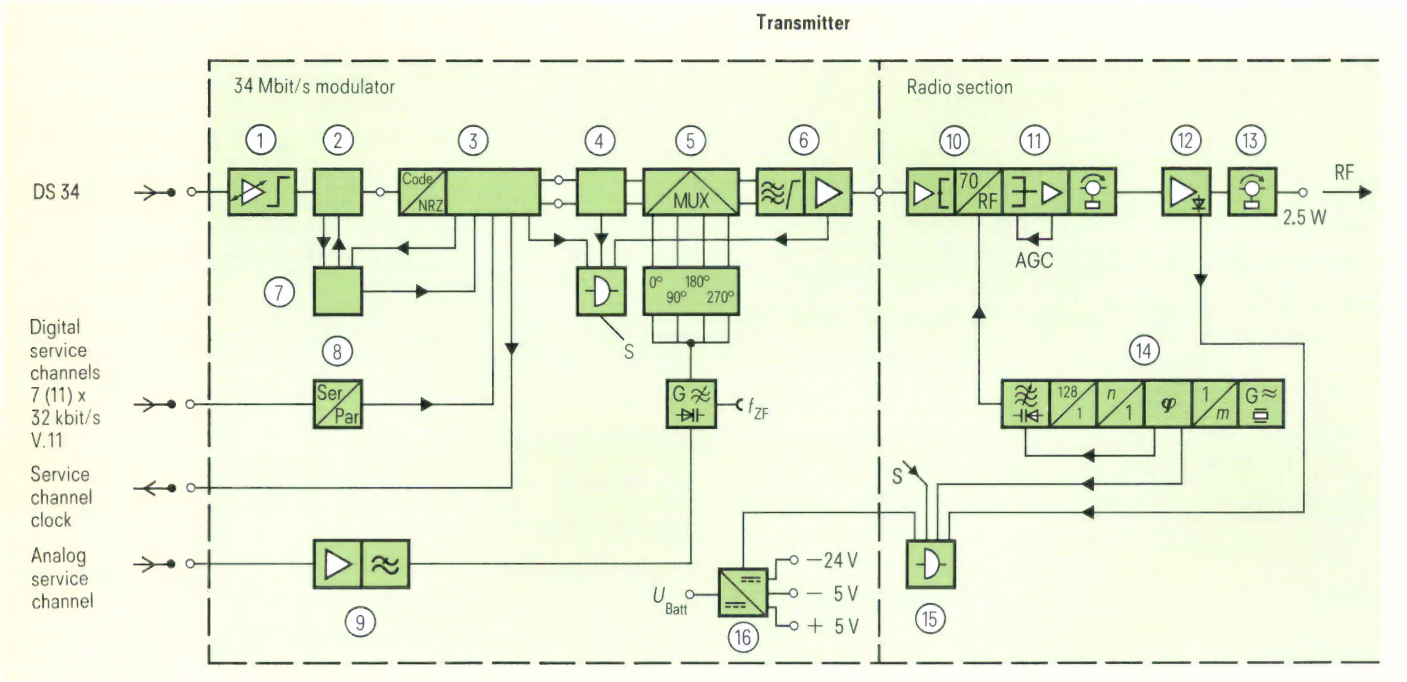


Fig. 1 Principle of quaternary phase-shift keying (QPSK) with offset

Modulation

The modulation scheme used is four-level phase-shift keying with offset. It belongs to that group of QAM schemes in which the two symbol streams in the in-phase and quadrature channels are mutually displaced by half a symbol period ($T/2$) [3]. With two-level symbols, this is obtained from an IF signal of largely constant envelope whose phase is changed at $T/2$ intervals to 0° or +90° or −90° (**Fig. 1**). However, in actual systems, a certain modulation of the envelope does occur as a function of the phase shifts. This envelope modulation is less significant with OQPSK than with conventional QPSK (quaternary phase-shift keying), as the critical 180° shifts are avoided by the offset method. Consequently, the OQPSK signal is largely immune to nonlinearities in the transmission path. By differentially encoding the transmit-side digital signal [4], the information is not transmitted in the absolute carrier phase but in the phase change. As a result, the QPSK signal is unaffected by the ambiguity of the carrier phase ($\pm n \times 90°$) during coherent demodulation on the receive side.

The advantage of transmitting digital signals is that they can be regenerated, thus eliminating interference and distortion. Consequently, where transmission quality and availability require it, the signal is demodulated, regenerated and then remodulated at each repeater station.



① Input amplifier with line equalizer
② Timing extraction
③ LSI device: decoder, scrambler and bit insertion*, "offset"
④ Differential encoding
⑤ 4PSK modulator (70 MHz) (PSK phase-shift keying)
⑥ Limiting amplifier
⑦ Line supervision
⑧ Serial-parallel converter
⑨ Input amplifier for analog service channel
⑩ Up-converter
⑪ RF preamplifier
⑫ RF output amplifier
⑬ Circulator
⑭ Carrier supply
⑮ Supervision
⑯ Power supply
* only at terminal stns.
AGC Automatic Gain Control
DS Digital signal
φ Phase discriminator
G Generator
IF Intermediate frequency
m Division factor
MUX Multiplexer
n Division factor
NRZ Nonreturn to zero
RF Radio frequency
S Supervision
U_{Batt} Battery voltage

Fig. 2 Functional diagram of transmitter in the DRS 34/1900-2400-2600 digital radio relay system

Design of the 34 Mbit/s OQPSK modem

In the modem, a radio relay system frame is superimposed on and subsequently removed from the digital signal to be transmitted. It enables digital service channels to be provided as well as internal system information and hop-related data to be transmitted.

The major part of the digital signal processing section in the modulator and demodulator is implemented in each case using a semicustom, large-scale integrated circuit in high-speed CMOS standard cell technology [5]. Compared with conventional solutions using discrete integrated circuits, this approach provides the advantages of a low power requirement, high reliability, compactness and high cost effectiveness. The modulator and demodulator are available either in the form of individual cassettes or as a self-contained modem equipment inset with two slide-in units for the modulator and demodulator. In the first case, the modulator cassette is integral with the transmitter and the demodulator cassette with the receiver (**Figs. 2** and **3**). In the second case, the modem inset, with its own supervision module, is connected to the radio equipment via a standard IF interface.

The following paragraphs describe the salient features of the electrical design of the modulator and demodulator.

Modulator (*Fig. 2*)

The 34.368-Mbit/s baseband signal supplied from a multiplex equipment in HDB3 code (high density bipolar of order 3) is first amplified and equalized in an input circuit, providing automatic compensation of cable losses up to 12 dB (at 17 MHz). The signal is then regenerated in a timing recovery circuit and separated according to polarity into two NRZ (nonreturn to zero) data streams with the associated timing. If required, an AMI (alternate mark inversion) interface can be used instead of the HDB3 interface.

The two data streams and the timing signal undergo further processing in a large-scale integrated circuit containing an HDB3 decoder (optionally AMI at repeater stations) with code rule supervision. If the HDB3 input signal exhibits a bit error ratio in excess of 1×10^{-3}, e.g. if the input level at the HDB3 interface is too low, a supervision circuit produces an alarm and injects an all-ones signal (AIS alarm indication signal). The decoded data are fed to an "elastic store" which, at terminal stations, performs a clock rate conversion in the ratio 547:537. A phase-locked loop with a "pullable" crystal-controlled oscillator (35.008 MHz) is connected to the integrated circuit for this purpose and to suppress jitter.

At repeater stations, the elastic store is used for jitter reduction only. In this case, the data stream is fed unprocessed to the output interface. At terminal stations, the NRZ signal that is converted to 35.008 Mbit/s in the elastic store contains the 10-bit gaps for each half-frame which are required for establishing the radio relay system frame. This enables seven digital service channels to be created. If required, the gap for each half-frame can be extended to 12 bits to provide eleven digital service channels.

The clock rate is then converted by the elastic store in the ratio 549:537, thereby increasing the output bit rate to 35.136 Mbit/s. The signal (apart from the gaps) is first scrambled in two different ways with a set, 7-bit long scrambler. One of the two resulting data streams is used for parity bit generation, the parity bit being added to the pairs of ones in each group of 537 data bits (half-frame) to make an odd number. In the other data stream, the gaps produced by clock rate conversion in the elastic store are filled by a multiplexer with system information such as the frame alignment signal, RF channel identification, parity bit and digital signal channels [6].

The data stream containing the framing information is then divided in the output circuit of the integrated device into two 17.504-Mbit/s NRZ data streams offset by half of one symbol period and fed as 2-bit symbols with associated timing to the actual phase modulator operating at the 70-MHz IF.

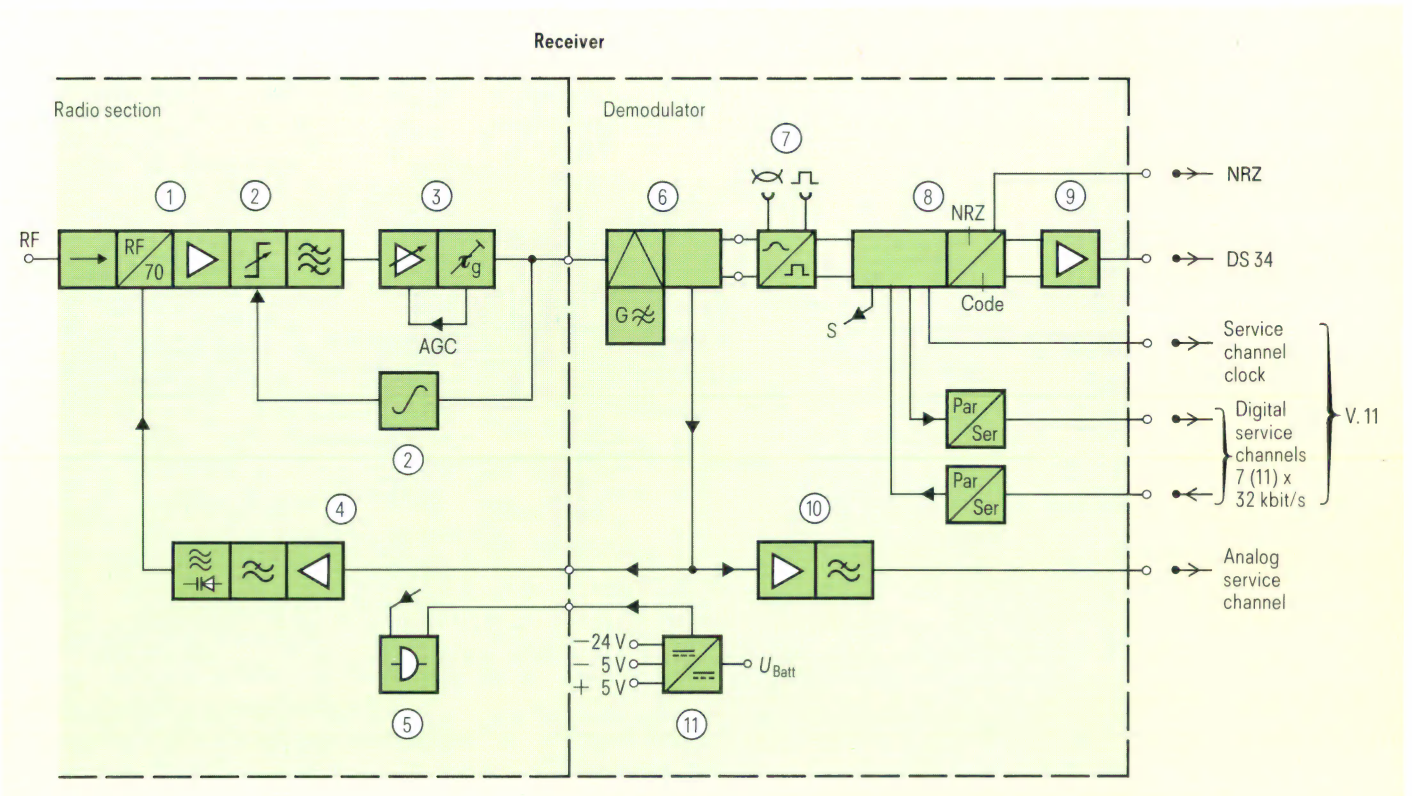
Differential encoding is performed at the input of the OQPSK IF modulator. The two differentially encoded, offset data streams are fed via a multiplexer to release the 70-MHz carrier in the appropriate phase for the 2-bit symbol applied. The signal is subsequently limited in both amplitude and spectrum and transferred to the radio equipment.

As the 70-MHz carrier can be frequency-modulated in the range from 0.3 to 16 kHz, it is possible to transmit up to four analog service channels in the usual 3.1 kHz bandwidth. Faults in the elastic store or in the OQPSK modulator and loss of the 35.008-MHz timing or framing result in an equipment fault signal.

Demodulator (*Fig. 3*)

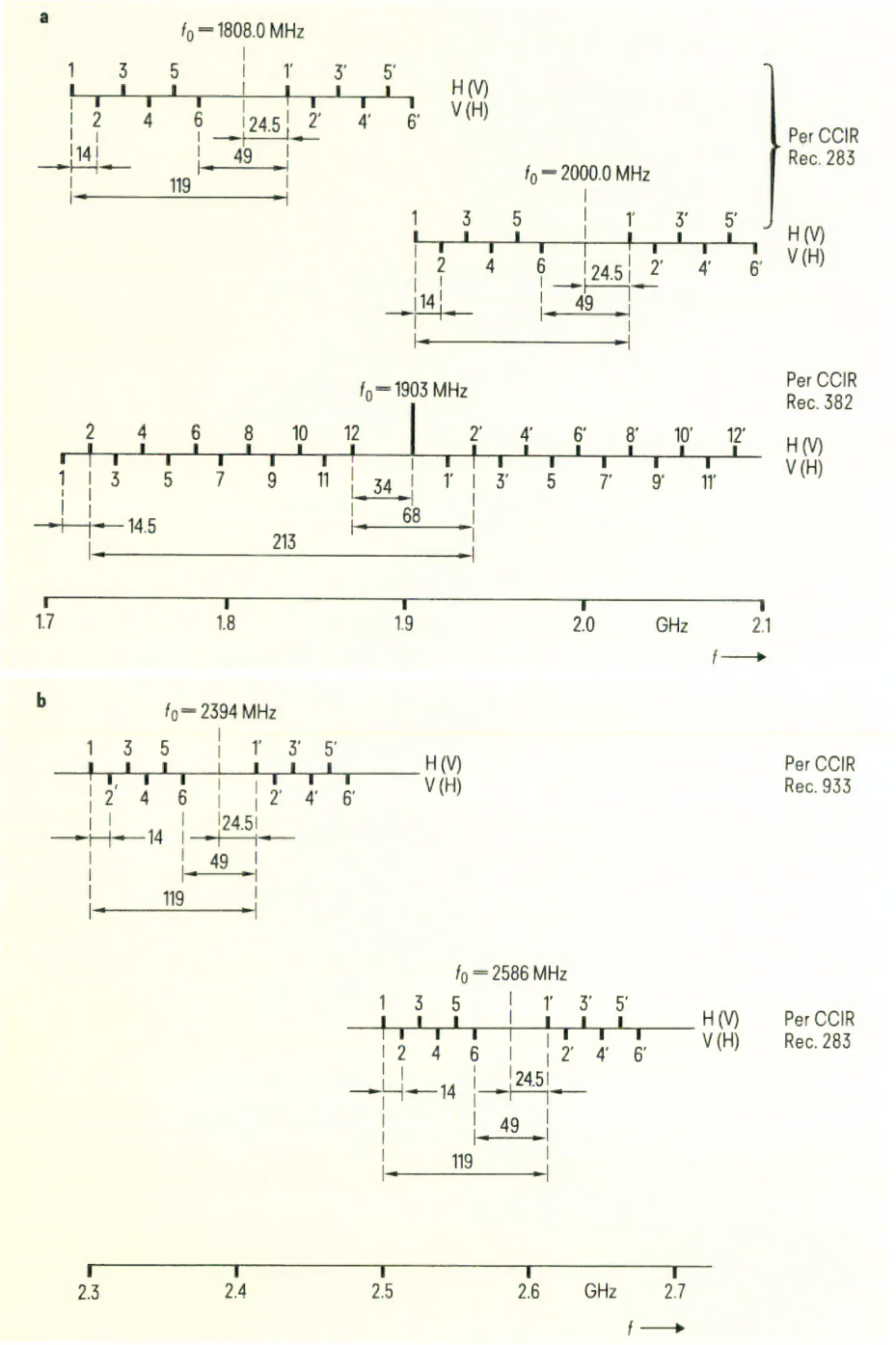
For coherent demodulation, the IF signal supplied from the receiver radio section is first amplified. The actual OQPSK demodulator consists of two multipliers fed with in-phase IF signals and with carriers recovered from the incoming IF signal and applied in quadrature via a 90° junction. This produces two bit streams which correspond to the two differentially encoded data streams preceding the output multiplexer in the OQPSK modulator. A "Costas loop" [7] generates a voltage for controlling the carrier oscillator, which then provides the recovered quadrature carriers in the correct phase for coherent demodulation. The control voltage additionally contains the demodulated analog service channel signal. Demodulation is followed by timing extraction, regeneration of the two bit streams and removal of the offset.

Digital processing of the two regenerated bit streams takes place in a large-scale integrated circuit in which differential decoding is first performed. This restores the data stream which was split up in the modulator in the form of two parallel bit streams of 17.504 Mbit/s each. At repeater stations, the data



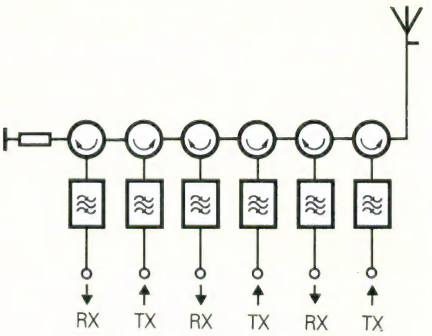
① Down-converter and IF preamplifier
② Adaptive equalizer
③ Main IF amplifier and delay equalizer
④ Carrier supply
⑤ Supervision
⑥ 4PSK synchronous demodulator with carrier recovery
⑦ Regenerator, timing extraction
⑧ LSI device: differential decoder, descrambler bit extraction, encoder
⑨ Binary-ternary converter with line driver
⑩ Output amplifier for analog service channel
⑪ Power supply
AGC Automatic gain control
DS Digital signal
G Generator
HDB3 HDB3 code (high density bipolar of order 3)
IF Intermediate frequency
NRZ Nonreturn to zero
RF Radio frequency
S Supervision
U_{Batt} Battery voltage

Fig. 3 Functional diagram of the receiver in the DRS 34/1900-2400-2600 digital radio relay system



f_0 Band center frequency
H Horizontal polarization
V Vertical polarization

Fig. 4 RF channel arrangement for the DRS 34/1900-2400-2600 family of digital radio relay systems for the radio-frequency (RF) bands 1.7 to 2.1 GHz (a) and 2.3 to 2.7 GHz (b)



RX Receiver
TX Transmitter

Fig. 5 Channel branching filter arrangement for the DRS 34/1900-2400-2600 family of digital radio relay systems

stream is passed on to the output circuit of the integrated device, while at terminal stations the radio relay frame is first removed. In both repeater and terminal station operation, the framing bits required for link supervision are detected in a signal branch with the aid of an alignment circuit. A circuit fault is signaled if the RF channel identification used in the demodulator does not coincide with that of the transmitted signal or if the bit error ratio exceeds 1×10^{-3} – in either case the receiver output produces an AIS signal. Parity violations result in error pulses which provide a measure of the bit error ratio and are also used to control the protection switching equipment during space diversity operation.

At terminal stations, the differentially decoded data stream is descrambled. In addition, the added bits for the digital service channels are extracted prior to removal of the radio relay frame and the associated conversion to the 34.368-Mbit/s interface bit rate (two bit streams of 17.184 Mbit/s each). If the demodulator is used at repeater stations with a service channel unit [6], it is possible for the digital service channels to be read and overwritten at these stations. At terminal stations, the bit stream, with the radio relay system frame removed, is fed to the output circuit of the integrated device. The output circuit separates the NRZ signal according to polarity into two NRZ bit streams in compliance with the HDB3 encoding law (optionally AMI at repeater stations). In the following circuit located outside the integrated device, the NRZ signals are converted to a ternary RZ signal which is then set to the level recommended in CCITT G.703 by a line driver amplifier.

DRS 34/1900-2400-2600 system family for the 2-GHz band with integral modem cassettes

RF channel arrangement

The DRS 34/1900-2400-2600 system family operates in RF bands between 1.7 and 2.1 GHz or 2.3 and 2.7 GHz with the RF channels arranged in accordance with CCIR Recommendations 283 and 382 or CCIR Report 933 (**Fig. 4**). Adjacent channels have a minimum frequency spacing of 14 (14.5) MHz and operate on a cross-polarized basis in order to achieve the required isolation. A frequency spacing of 28 (29 MHz) is provided if co-polarization is employed.

Transmitter radio section

The phase-shift-keyed IF signal is fed via an IF amplifier to a single-sideband up-converter (**Fig. 2**). Image frequency and residual oscillator signals are suppressed such that the following RF transmit amplifiers can operate without additional image frequency rejection. The up-converter is immediately followed by the RF transmit amplifier which produces 2.5 W at the transmitter output in the DRS 34/1900 system and 1 W in the DRS 34/2400-2600 system. Owing to the use of OQPSK, the amplifier output stages can operate in class C without system degradation, thus reducing the power consumption.

Carrier supply

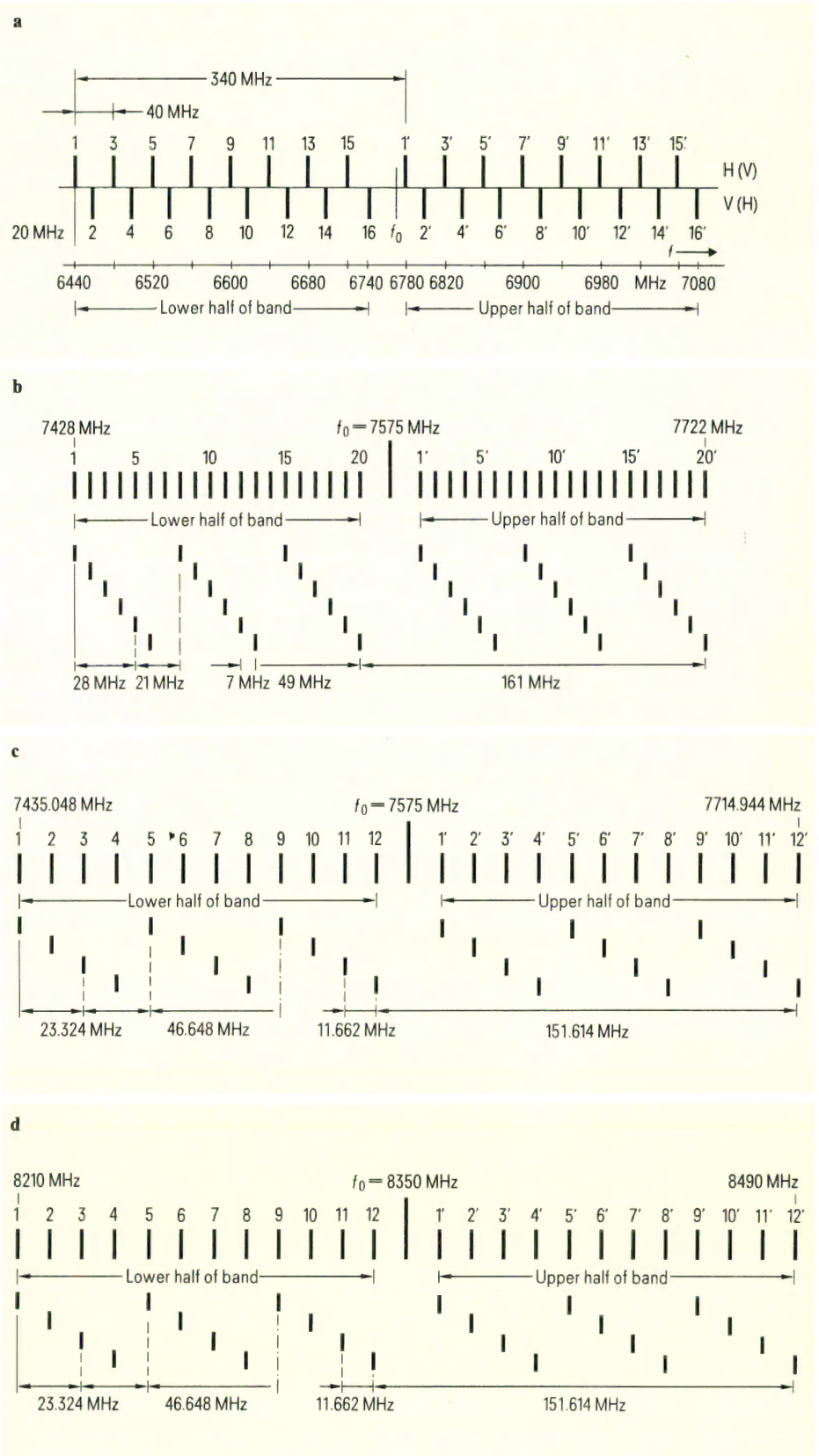
The transmit and receive oscillators have the same RF oscillator incorporating a bipolar transistor. It is stabilized by a synthesizer circuit in the transmitter (**Fig. 2** and **3**). The synthesizer circuit controls the frequency of the transistor oscillator which is tunable across the entire RF band. A programmable digital divider is used for this purpose to divide the radio frequency down to about 2 kHz. The frequency of a 4-MHz crystal-controlled reference oscillator is divided down to the same value. The output voltage of a phase discriminator to which both the signals are fed is used as the control criterion for adjusting the RF oscillator. The oscillator frequency can be set in 0.5-MHz increments by varying the division ratio in the programmable divider. The receive oscillator frequency is adjusted via the carrier recovery loop of the demodulator using the 70-MHz intermediate frequency as a control criterion.

Channel branching filter

Up to six transmitters and receivers can be connected to one antenna via the channel branching filter (**Fig. 5**). The transmitters and receivers can be connected alternately to a common branching filter chain. The channel branching filters are designed as six-section resonator filters [8] with a 3-dB bandwidth of 24 MHz.

Receiver radio section

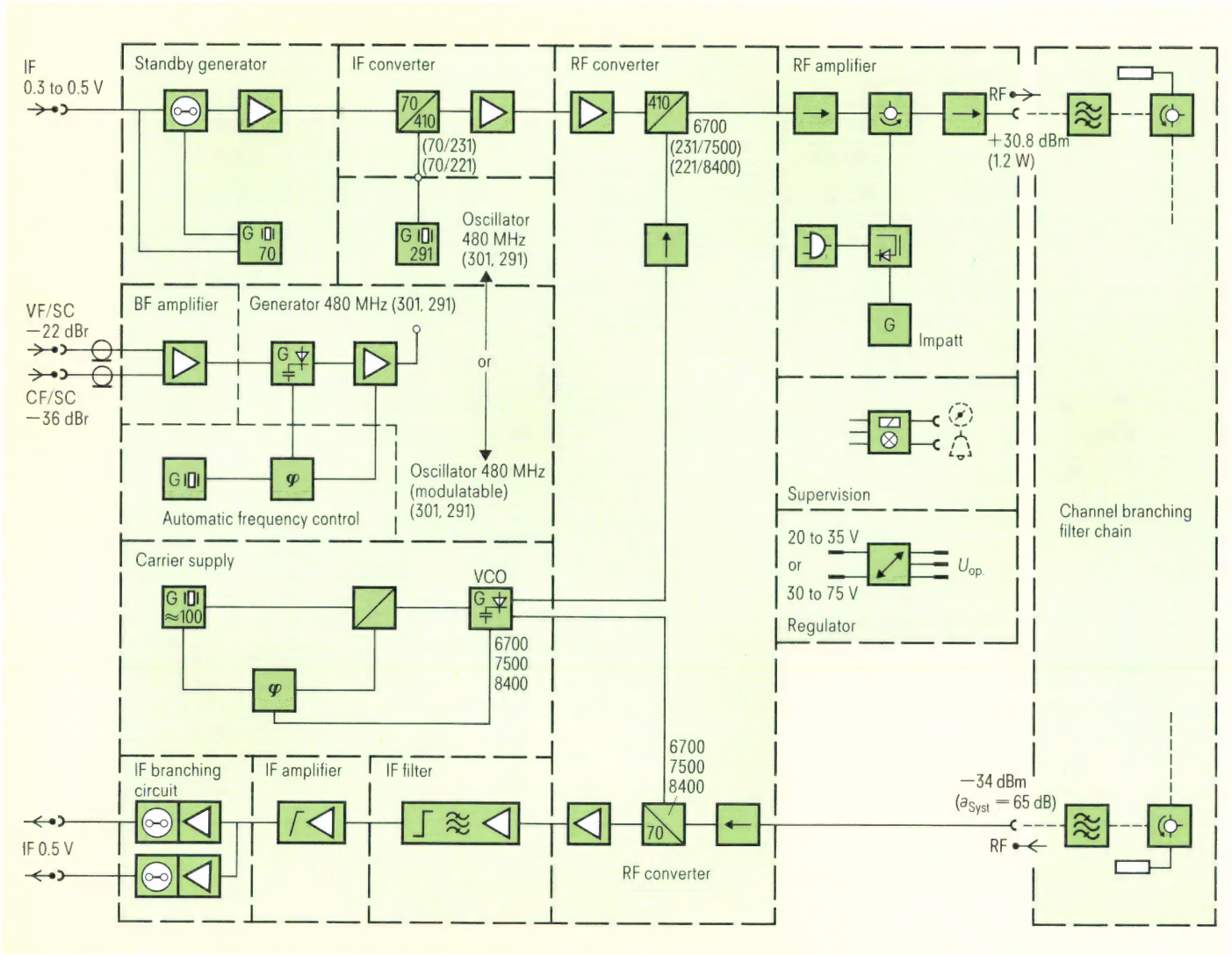
In the DRS 34/2400-2600 systems, the receive signal first passes through a low-noise RF preamplifier and a single-sideband down-converter (noise figure



f_0 Band center frequency
H Horizontal polarization
V Vertical polarization

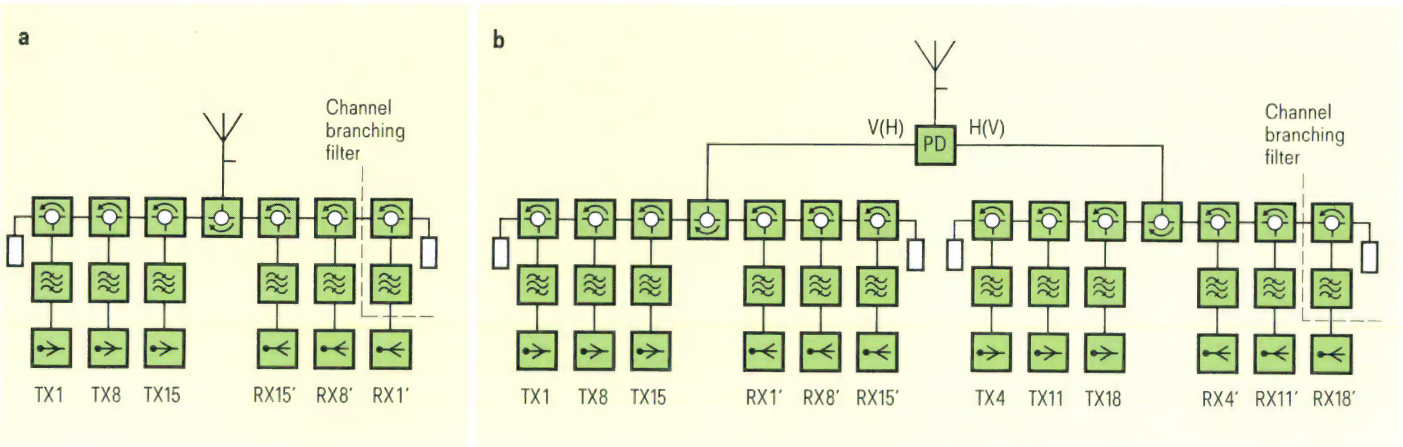
Fig. 6 RF channel arrangement for the DRS 34/6700-7500-8400 family of digital radio relay systems for the radio (RF) bands 6.425 to 7.125 GHz, 7.425 to 7.725 GHz and 8.2 to 8.5 GHz

a per CCIR Recommendation 384
b per CCIR Recommendation 385 (top) and 386 (bottom)
c per CCIR Recommendation 386



a_{Syst}	System loss	φ	Phase discriminator	SC	Service channel
BF	Baseband frequency	G	Generator	VCO	Voltage-controlled oscillator
CF	Carrier frequency	IF	Intermediate frequency	VF	Voice frequency
		RF	Radio frequency		

Fig. 7 Functional diagram for the DRS 34/6700-7500-8400 family of digital radio relay systems



H	Horizontal polarization	RX	Receiver	V	Vertical polarization
PD	Polarization diplexer	TX	Transmitter		

Fig. 8 Channel branching filter arrangement for the DRS 34/7500 digital radio relay system

a Three RF channel pairs on one antenna (channel arrangement per CCIR 385)

b Six RF channel pairs on one antenna

$F \leq 4$ dB). In the DRS 34/1900 system (**Fig. 3**), the receiver begins with a wideband balanced converter ($F \leq 7$ dB); the following IF preamplifier is used simultaneously as an adaptive equalizer for attenuation amplitude slopes of up to $\pm$ 10 dB at $\pm$ 10 MHz. An amplitude discriminator at the output of the IF section supplies the control criterion for automatic compensation of signal distortion due to selective fading. At the output of the IF preamplifier with a 3-dB bandwidth of 22 MHz, a band-pass filter limits and shapes the signal spectrum to provide a minimal background error ratio.

Variations in input level between -30 and -84 dBm are compensated by the main IF amplifier. The group delay distortion introduced by the filters is compensated in the following three-section active group delay equalizer. Differences in group delay distortion due to the different number and sequence of the channel branching filters can be compensated with various fixed settings of the delay equalizer. For this purpose, the individual all-pass filters contain varactor diodes whose bias voltages can be varied by switchable voltage dividers.

DRS 34/6700-7500-8400 system family with separate equipment insets for radio section and modem

The DRS 34/6700-7500-8400 series comprises three radio relay systems of identical mechanical design. The following paragraphs describe the electrical design of the transmitter and receiver (after details concerning the RF channel arrangements) and provide details of the carrier supply and channel branching filter arrangement.

RF channel arrangements

The three systems of this equipment family operate in the RF bands, 6.425 to 7.125 GHz, 7.425 to 7.725 GHz and 8.2 to 8.5 GHz with the RF channels arranged in accordance with CCIR Recommendations 384, 385 and 386, as shown in **Fig. 6.** Adjacent channels have a minimum frequency spacing of 20, 21 or 28 and 23.3 MHz when operated on a cross-polarized basis. With co-polarization of adjacent channels, the arrangement provides for frequency spacings of 40, 49 and 46.6 MHz.

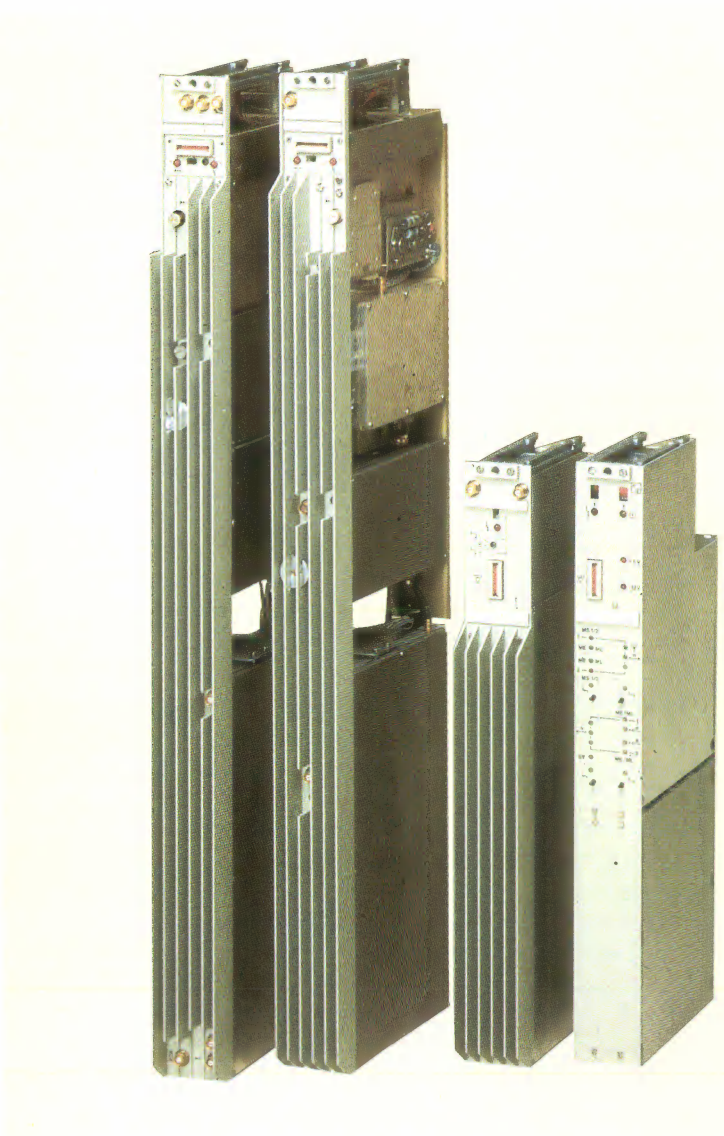


Fig. 9 Transmitter and receiver of the 34/1900-2400-2600 family of digital radio relay systems (left) and protection switching equipment (right)

Fig. 10 Radio unit of the DRS 34/6700-7500-8400 family of digital radio relay systems

Transmission rate		34.368 Mbit/s					
Number of voice circuits		480					
Bandwidth of analog service channel		0.3 to 16 kHz					
No. of digital service channels		7 (11)					
Bit rate of a digital service channel		32 kbit/s					
Modulation scheme		4 PSK offset, differentially encoded					
Frequency bands	GHz	1.7 to 2.1	2.3 to 2.5	2.5 to 2.7	6.42 to 7.10	7.42 to 7.73	8.20 to 8.50
RF channel arrangement per CCIR		283 (382)	Rep.933	283	384	385	386
Minimum channel spacing	MHz	14 (14.5)	14	14	20	21/28	23.3
Number of RF channel pairs		6 (12)	6	6	16	6/5	6
Transmit power	W	2.5	1	1	1.2	1.2	1.2
Receiver noise figure	dB	≤7	≤4	≤4	≤8	≤8	≤8
Control range of receive level	dBm	−30 to −83	−30 to −86	−30 to −86	−28 to −85	−28 to −85	−28 to −85
Receive level for *BER* of 1×10^{-3}	dBm	≤−80	≤−83	≤−83	≤−80	≤−80	≤−80
Flat fading margin	dB	39	42	42	46	46	46
System gain	dB	114	113	113	111	111	111
Spectrum efficiency	$\frac{\text{bit/s}}{\text{Hz}}$	2.5	2.5	2.5	1.7	1.6/1.2	1.5

BER Bit error ratio RF Radio frequency PSK Phase-shift keying

Table Principal characteristics of digital radio relay systems, DRS 34/1900-2400-2600 and DRS 34/6700-7500-8400

Transmitter radio section (*Fig. 7*)

At the transmitter input, the phase-shift-keyed IF signal from the modulator or – in the case of IF through-connection – from the preceding receiver first passes through a supervision circuit. If the IF voltage drops to 0.15 V, the IF signal input is automatically disconnected and a 70-MHz standby generator is simultaneously switched to the transmitter input so that the RF carrier is maintained on the route.

In the following IF converter, the first intermediate frequency of 70 MHz is translated to the second IF of 410, 231 or 221.6 MHz. This additional conversion to a high second IF is necessary in order to obtain the standard transmit-receive separation (**Fig. 6**), as the transmitter/receiver unit of this series of systems employs only one microwave carrier supply. The IF signal at the second IF is amplified and fed to the transmit mixer in the RF-converter module where it is translated to RF by heterodyning with the carrier frequency. An injection-locked, single-stage RF amplifier raises the RF signal to an output power of approximately 1.2 W. The RF amplifier also includes facilities for supervising the output power and the locking of the input and output frequencies. Loss of lock results in automatic disconnection of the transmit path.

Receiver radio section (*Fig. 7*)

The receive signal is fed via the channel branching filter chain to the receiver input. Following translation to the 70-MHz IF in the receive mixer of the RF-converter, the signal passes through a low-noise IF preamplifier. The IF filter module contains the receiver's entire IF selectivity and an adjustable equalizer for compensating the delay distortion introduced by the entire transmission path. The equalized IF signal is then amplified in a limiting IF amplifier and split between two identical, mutually isolated outputs in the IF branching unit. The second output is available for test purposes. Both outputs are electronically disconnected if the automatic receive level supervision unit is activated in response to an excessively low input level.

Carrier supply

The transmitter and receiver have a common carrier supply. The frequency of a free-running Gunn oscillator is compared via a phase-locked loop with that of a crystal-controlled oscillator operating at about 100 MHz, and any deviation is corrected. The transmit and receive mixers in the RF converter are fed with the carrier required for conversion via the two mutually isolated outputs of the carrier supply.

Since the carrier used to translate the 410, 231 or 221.6 MHz IF signal in the transmit mixer is the same as that used in the receive mixer to translate the RF receive signal to the 70 MHz IF, a spacing of 340, 161 or 151.6 MHz is obtained between the transmit and receive frequencies (**Fig. 6**). If the frequency control circuit of the carrier supply is defective, the transmit and receive paths are disconnected.

Channel branching filters (*Fig. 8*)

When several transmitters and receivers are operated on a common antenna, the transmitter outputs and receiver inputs are combined via branching filter arrangements. Each transmitter and receiver is assigned a channel branching filter comprising a band-pass filter and a circulator. The band-pass filter – a four- or six-section filter – will only pass the frequency band of the associated RF channel. All the frequencies outside this band are reflected and passed on to the next branching filter by the circulator. Up to three or four transmitters or receivers are interconnected via a channel branching filter chain, the end of which is connected to a low-reflection termination. The channel branching filter chains of the transmitters and receivers are connected to the antenna via a circulator and a common waveguide. If more than three or four channel pairs are operated on one antenna, the transmit and receive channel branching filter chains combined via the circulator are connected to a common antenna via a polarization diplexer (PD).

Mechanical design of the radio equipment of both system families

As mentioned earlier, in the DRS 34/1900-2400-2600 family of systems the transmitter and modulator cassettes or the receiver and demodulator cassettes are incorporated in one equipment inset. The insets employed for this purpose are narrow style 7R Type III insets, measuring 54 mm wide by 800 mm high (**Fig. 9**).

By contrast, in the DRS 34/6700-7500-8400 family of systems operating in the 6.4 to 8.5 GHz band, the radio equipment and modem are provided in separate insets. The transmitter and receiver are installed in a common style 7R Type II equipment inset , measuring 110 mm wide by 600 mm high (**Fig. 10**). The modulator and demodulator are each located in a style 7R Type III equipment inset, measuring 54 mm wide by 500 mm high.

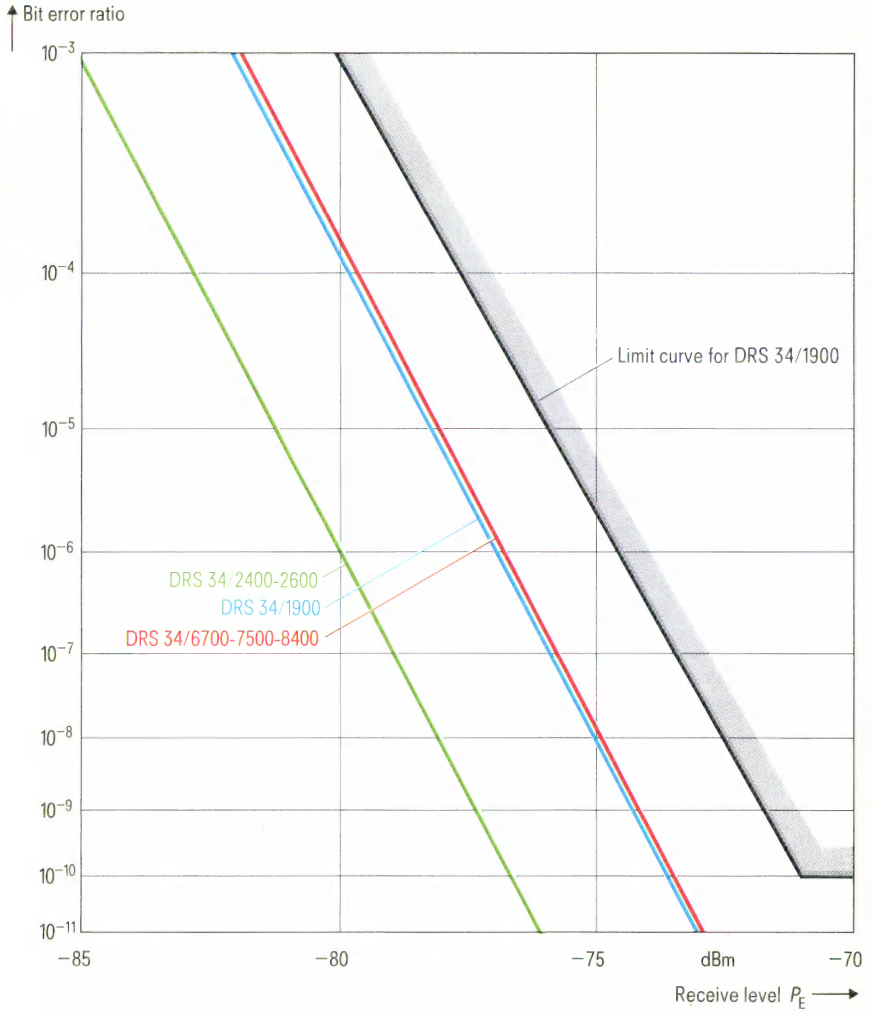
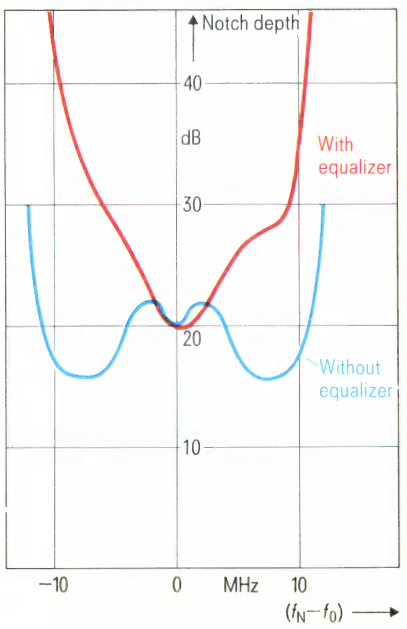


Fig. 11 Measured bit error ratio (*BER*) as a function of the receive level P_E



f_0 Band center frequency f_N Notch frequency

Fig. 12 Measured signature curves of the DRS 34/1900-2400-2600 family of digital radio relay systems (minimum phase at $\tau = 6.3$ ns and $BER = 1 \times 10^{-3}$)

System data and test results

The **Table** lists the principal characteristics of both radio relay system families. In addition, **Fig. 11** shows the measured bit error ratio as a function of the receive level for the individual systems. The parallel displacement of the individual system curves is due to the different typical receiver noise figures and the different degradations. The theoretical values are achieved to a good approximation.

Fig. 12 shows measured signature curves of the DRS 34/1900-2400-2600 series of

systems. The signature is considerably enhanced by a simple adaptive slope equalizer in the IF preamplifier. Since the isolation provided by cross-polarization is utilized for the relatively closely spaced adjacent channels, it is not possible to implement cochannel operation on the same route. On intersecting routes, the transmitters of a station can be operated on a cochannel basis, provided that the sidelobe attenuation of the antennas is greater than 30 dB.

Summary

With the two system families in the 2 GHz RF bands and in the 6.7, 7.5 and 8.4 GHz band, a total of six radio relay systems in the frequency range from 1.7 to 8.5 GHz are available for 34 Mbit/s transmission in the long-haul network. The equipments feature very good electrical characteristics and a compact design. This means that long-haul networks with medium traffic volumes can be flexibly matched to transmission capacity.

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QAM Digital Radio Relay Modems for the Transmission of 140-Mbit/s Signals

An important objective in the transmission of 140-Mbit/s signals over radio relay links in the long-haul, medium-haul and short-haul network is to make efficient use of the limited frequency band available. This has to be traded off against another equally important objective, equipment economy. An optimal compromise within the various constraints (RF channel arrangement, frequency range, quality and availability requirements) is achieved with the aid of multilevel quadrature amplitude modulation (QAM) [1]. The implementation of digital radio modems (DRM) for such complex transmission methods requires the use of advanced technologies and methods.

The processing of digital signals at baseband, such as framing, synchronizing, encoding and decoding, scrambling and descrambling, etc., is based on bipolar semi-custom monolithic integrated circuits. The functional units are realized in modular form to allow their use in all members of the modern family, i.e. the 4-QAM (DRM 140/140-4), the 16-QAM (DRM 140/140-16) and the 64-QAM (DRM 140/70-64) modems.

Pulse and spectrum shaping at an intermediate frequency of 140 or 70 MHz is effected in accordance with the Nyquist criterion using surface acoustic wave (SAW) filters.

Multilevel modulation methods, especially with 16 and more levels, are increasingly sensitive to time-variant linear distortion caused by the transmission channel as a result of multipath propagation (dispersive fading). The receive channel requires adaptive equalization for this reason.

The 16-QAM demodulator is optionally equipped with an adaptive baseband equalizer while the 64-QAM demodulator inset contains such an equalizer as a standard feature. The equalizer is designed as a complex transversal filter with one additional quantized feedback loop. Because its coefficients are controlled by time-domain criteria, it is what is known as an adaptive time-domain equalizer (ATDE). The equalizer structure and the control algorithm employed are determined not only by the channel model, but also to a large extent by the technology adopted. High-precision analog modules in hybrid integrated thin-film and thick-film technology are of considerable importance alongside monolithic integrated silicon technology in this application.

To increase the bandwidth efficiency of a given QAM system by a factor of two, the cochannel/orthoganal polarization operation must be employed. For 16 or more levels a cross-polarization interference canceller (XPIC) may be necessary to provide the required transmission quality. Therefore, the 16-QAM and the 64-QAM demodulators are equipped with the corresponding interfaces to cooperate with such a canceller.

The results obtained with conventional and new measuring procedures for the 4-QAM, 16-QAM and 64-QAM modems are discussed.

The new procedures are aimed particularly at the dynamic response and the tracking and acquisition capability of the adaptive equalizer.

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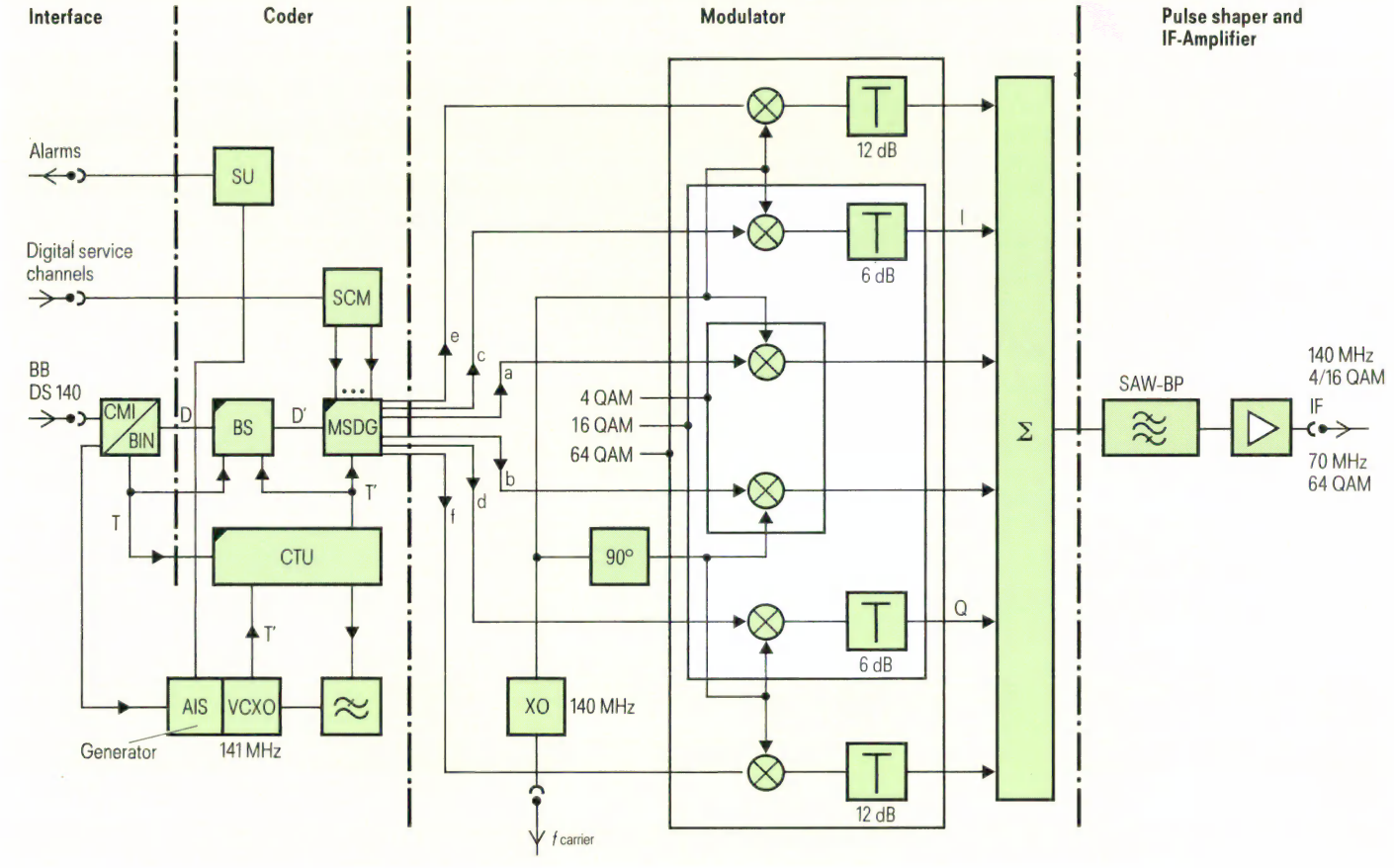


	Semi-custom monolithic integrated circuit (gate array)	D	Binary NRZ signal (nonreturn-to-zero)	QAM	Quadrature amplitude modulation
a, b, c, d, e, f	2/4/6-bit symbols	D'	Converted and dejittered NRZ signal	SAW-BP	Surface accoustic wave band-pass filter
AIS	Alarm indication signal	DS 140	Digital signal at 139.264 or 141.475 Mbit/s	SCM	Service channel multiplexer
BB	Baseband	IF	Intermediate frequency	SU	Supervision
BIN	Binary code	I, Q	Quadrature channels	T	Recovered timing
BS	Buffer storage	MSDG	Multiplexer, scrambler and differential / Gray encoder	T'	Converted and dejittered timing
CMI	CMI code (coded mark inversion)			VCXO	Voltage-controlled crystal oscillator (141.475 MHz)
CTU	Central timing unit			XO	Crystal oscillator (140 MHz)

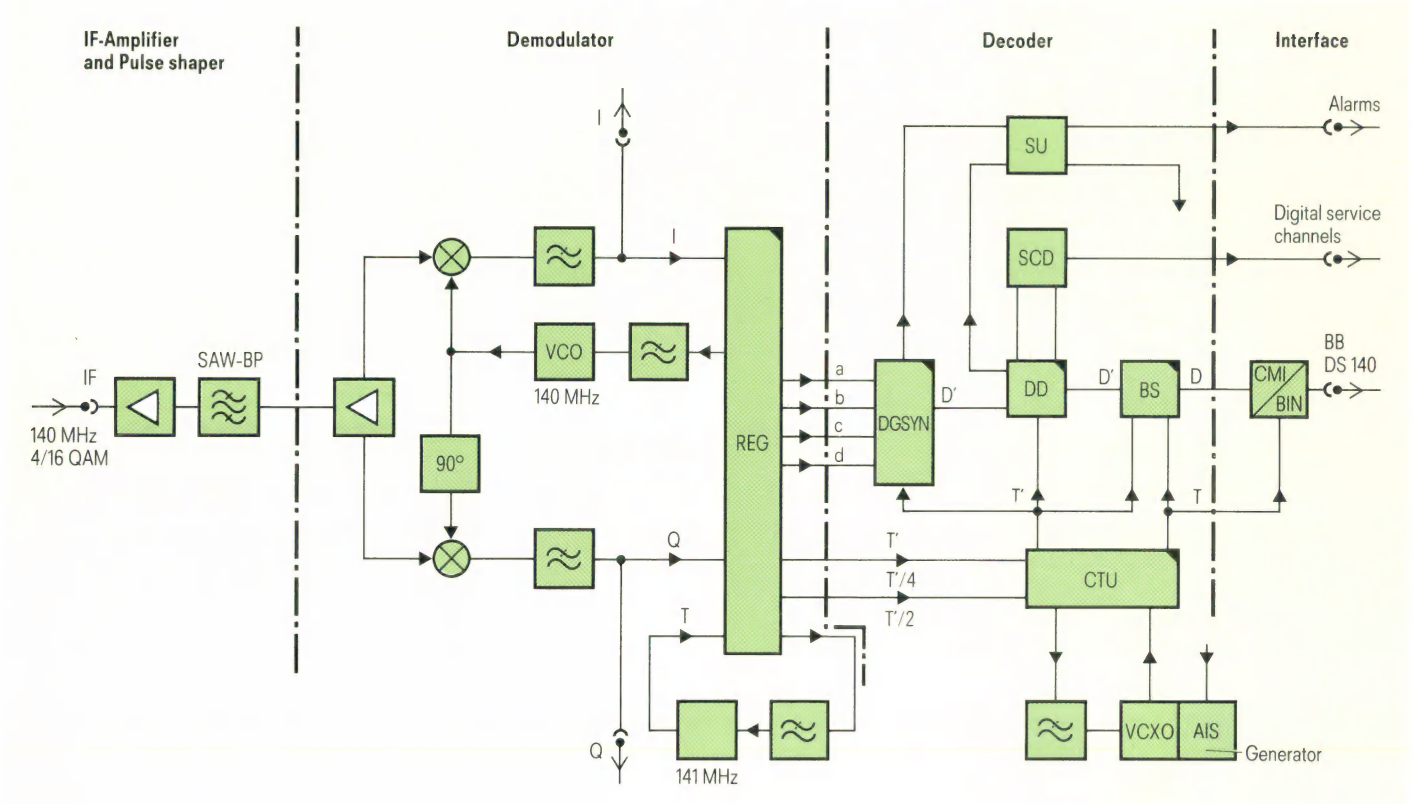
Fig. 1 Functional circuit diagram of the modulator inset for 4, 16 or 64 QAM

System Concept

The family of digital radio systems described in [2] employs the DRM 140/140 – 16 modem equipment (with and without ATDE) to transmit 140-Mbit/s signals in long-haul and medium-haul telecommunication networks. The required bandwidth efficiency to accommodate one 140-Mbit/s signal in a 40-MHz interleaved channel allocation plan and 28-MHz interleaved spacing for long-haul and medium-haul application, respectively, is achieved with 16 QAM. In the 40-MHz channel pattern there is the option of doubling the bandwidth efficiency from 3.5 bit/s/Hz to 7 bit/s/Hz by employing cochannel operation using both orthogonal polarizations of the same radio frequency. For long-haul transmission of 140 Mbit/s in 28-MHz and 29.65-MHz frequency patterns the DRM 140/70-64 (always with ATDE) is used with digital radio systems described in [3]. The cochannel option for doubling the capacity of the occupied frequency band is also available in here. The use of cancellers (XPICs) [4] will be a necessity in these cases.

The 4-QAM version of the modem equipment has been designed for short-haul applications at high radio frequencies (e.g. 18.7 GHz [5]). It can also be used for outdoor operation in a weatherproof housing mounted near the antenna. The bandwidth efficieny of this 18.7-GHz system is increased by the use of 16 QAM for the transmission of 140 Mbit/s with 55-MHz channel spacing, instead of 110 MHz. To further increase the economy of the system, a 2 × 140 Mbit/s version of the 16-QAM modem, based on the functional units described in the subsequent sections, will be introduced soon, and will be described in detail in a future publication. This modem allows the transmission of 2 × 140 Mbit/s with a channel spacing of 110 or 80 MHz; it will also enable cochannel operation [5].

In all modem versions mentioned above, the required pulse and spectrum shaping is effected at an intermediate frequency of either 140 MHz or 70 MHz in accordance with the Nyquist criterion [6] and is optimally partitioned between the modulator and demodulator insets [7]. This also defines the interfaces to the transmit and receive radio units.



	Gate array	D'	Converted and dejittered NRZ signal	SAW-BP	Surface acoustic wave band-pass filter
a, b, c, d	2/4-bit symbols	DD	Demultiplexer, descrambler	SU	Supervision
AIS	Alarm indication signal	DS 140	Digital signal at 139.264 or 141.475 Mbit/s	T'	Recovered timing
BB	Baseband	DGSYN	Differential/Gray decoder and synchronizer	T	Converted and dejittered timing
BIN	Binary Code	IF	Intermediate frequency	VCO	Voltage-controlled oscillator (140 MHz)
CMI	CMI code (coded mark inversion)	I, Q	Quadrature channels	VCSO	Voltage-controlled SAW oscillator (141.47 MHz)
CTU	Central timing unit	QAM	Quadrature amplitude modulation	VCXO	Voltage-controlled crystal oscillator (139.264 MHz)
D	Binary NRZ signal (nonreturn-to-zero)	REG	Carrier and timing signal recovery and regeneration		

Fig. 2 Functional circuit diagram of the demodulator inset for 4 and 16 QAM (without ATDE)

A system radio relay frame provides capacity not only for hop-related and internal system data but also digital service channels. These channels can be used for operating an $(N+1)$ protection switching equipment [8] and as a telephone or data link between radio relay stations [8]. They also enable information provided by the modem and radio units relating to transmission quality and availability to be forwarded for evaluation to a central location at the end of a radio link.

The 16-QAM demodulator inset is available in two versions, i.e. with or without adaptive baseband equalizer. The version with the transversal equalizer adapting to criteria derived in the time domain is employed particularly on unfavorable radio hops with a high incidence of multipath fading. The performance of the baseband equalizer as a means of maintaining transmission quality is most beneficial where the echo delay times are relatively long and there is nonminimum phase fading. In addition, this equalizer obviates the need for space diversity otherwise generally required by short hops with less frequent multipath fading. The version without equalizer, on the other hand, is preferred for economic reasons wherever quality and availability allow.

The two versions of the 16-QAM demodulator inset are compatible both electrically and mechanically and can, therefore, be easily interchanged.

Modulator and demodulator insets can be readily set for both terminal station and repeater station operation. The baseband interface signals are always CMI (coded mark inversion) encoded in accordance with CCITT Recommendation G.703, thus, greatly facilitating station layout and equipment operation. The latest technologies (SAW devices [10], semi-custom monolithic integrated circuits [11], hybrid integrated thin-film and thick-film circuits) are employed in realizing the modem family in order to achieve low-dissipation, space-saving, reliable and economical design. A crucial factor here was the extent to which it was possible to apply automation to the production and testing of the modules and equipment insets.

Digital Processing in the Baseband

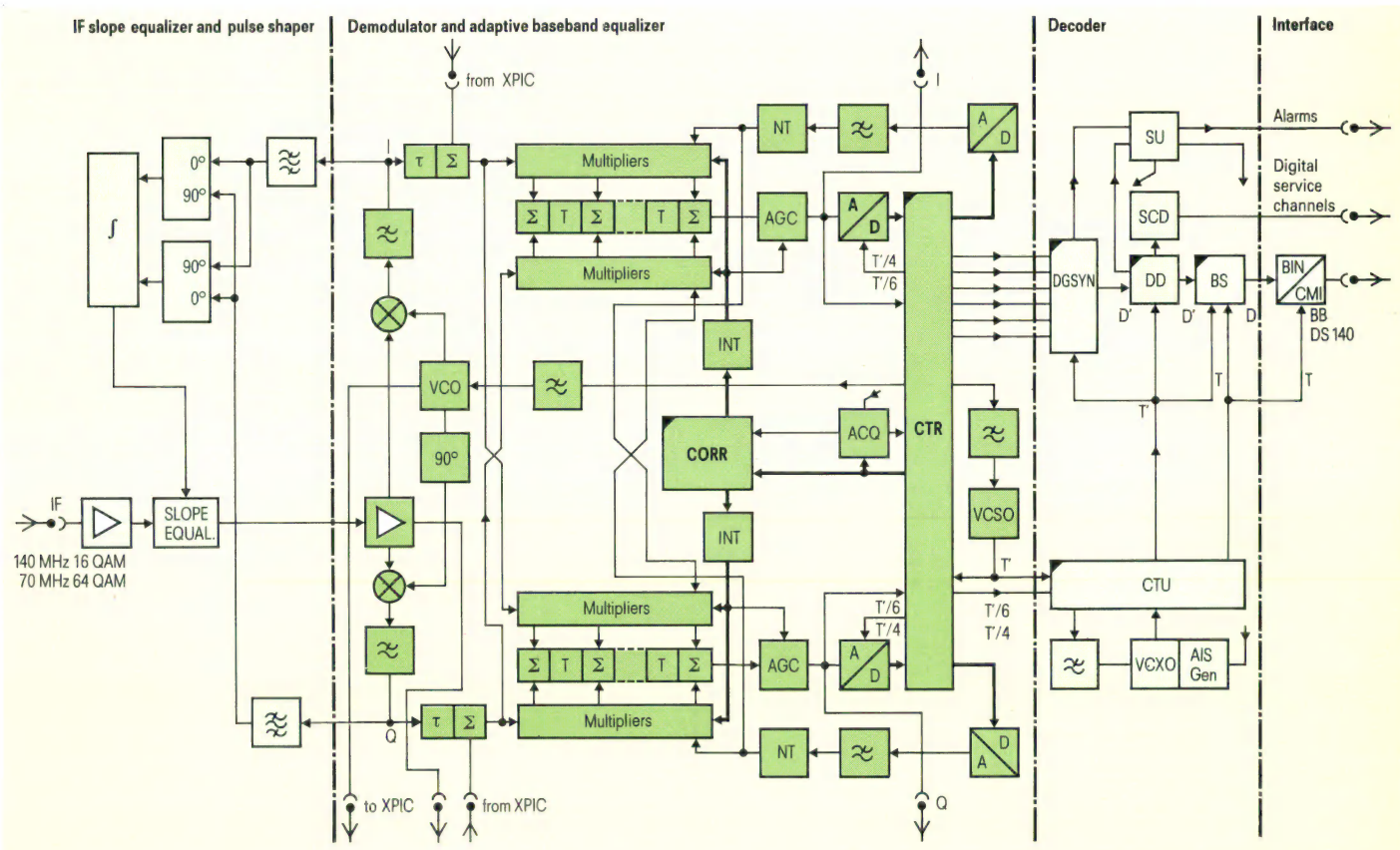
Modulator (interface and digital processing circuit)

The digital signal (139.264 kbit/s) arriving at terminal stations in CMI code is first equalized in the interface ($\sqrt{f}$ response of the cable attenuation), amplified and regenerated with the aid of the recovered timing signal (T) (**Fig. 1**). It is fed as a binary nonreturn-to-zero

(NRZ) signal with the associated timing to the digital processing circuit. The timing rate is converted by this circuit in the ratio 64/63 with the aid of the buffer storage (BS) and central timing unit (CTU) devices, which are designed as bipolar semi-custom integrated circuits in emitter-coupled logic (ECL) technology [11, 12]. The resultant phase-locked loop with voltage-controlled crystal oscillator (141-MHz VCXO) provides a high Q ($\approx 300{,}000$) with corresponding suppression of the input jitter. The converted NRZ signal, D′, and its associated 141.475-kbit/s timing signal, T′, then have the gaps required to form the system multiframe. These gaps are filled with internal system information (frame alignment signal, frame marking, channel identification) and digital service channels [9] by the monolithic integrated multiplexer/scrambler/differential-or-Gray-encoder (MSDG) unit.

These same gaps are scrambled by a set scrambler (11 bits long) and provided with a parity bit (every 504 data bits) for fault detection. The subsequent differential encoding [13], which is designed for minimum error propagation, has the effect of making the transmitted signal stream insensitive to the carrier phase states, locking in $n \cdot 90°$ varying states during coherent demodulation. The digital signal, D′, thus processed, is converted from serial to parallel format with 2, 4 or 6 bits per symbol ($2^2 = 4$ QAM, $2^4 = 16$ QAM, and $2^6 = 64$ QAM) and passed on at a symbol rate of 70 (1/2 · 141.475), 35 (1/4 · 141.475) or 23 Mbauds (1/6 · 141,475) to the quadrature modulator (a, b; a, b, c, d; or a, b, c, d, e, f). It is also possible to switch the modulator from the commonly used differentially encoded operation to a Gray encoded one, in this way avoiding the error multiplication factors (2, 5/3 or 10/7) associated with differential encoding. The fourfold phase ambiguity of the recovered carrier in the demodulator must then be resolved, e.g. by making use of redundancy present in the frame.

If the modulator is employed at a repeater station, a digital signal is applied to its baseband input, again in CMI format, but with a 141.475-kbit/s timing signal and framing already inserted. The framing is handed on, i.e. is left unchanged. Nevertheless, the jitter



	Semi-custom monolithic integrated circuit (gate array)	CTU	Central timing unit	SAW-BP	Surface acoustic wave band-pass filter
a, b, c, d, e, f	2/4/6-bit-symbols	D′	Binary NRZ signal (nonreturn-to-zero)	SCD	Service channel demultiplexer
A/D	Analog-digital converter	D	Converted or dejittered NRZ signal	SU	Supervision
AGC	Automatic gain control	DD	Demultiplexer and descrambler	T′	Recovered timing
AIS	Alarm indication signal	DS 140	Digital signal at 139.264 or 141.475 Mbit/s	T	Converted and dejittered timing
ACQ	Acquisition	DGSYN	Differential/Gray decoder and synchronizer	VCO	Voltage-controlled oscillator (140 MHz)
BB	Baseband	IF	Intermediate frequency (140 MHz)	VCSO	Voltage-controlled SAW oscillator (141.475 MHz)
BIN	Binary code	I, Q	Quadrature channels	VCXO	Voltage-controlled crystal oscillator (139.264 MHz)
BS	Buffer storage	INT	Integrator circuit	XPIC	Cross-polarization interference canceller
CMI	Coded mark inversion	CORR	Correlator	τ	Delay element
CTR	Carrier and timing recovery	QAM	Quadrature amplitude modulation		

Fig. 3 Functional circuit diagram of the demodulator inset for 16 and 64 QAM (with ATDE)

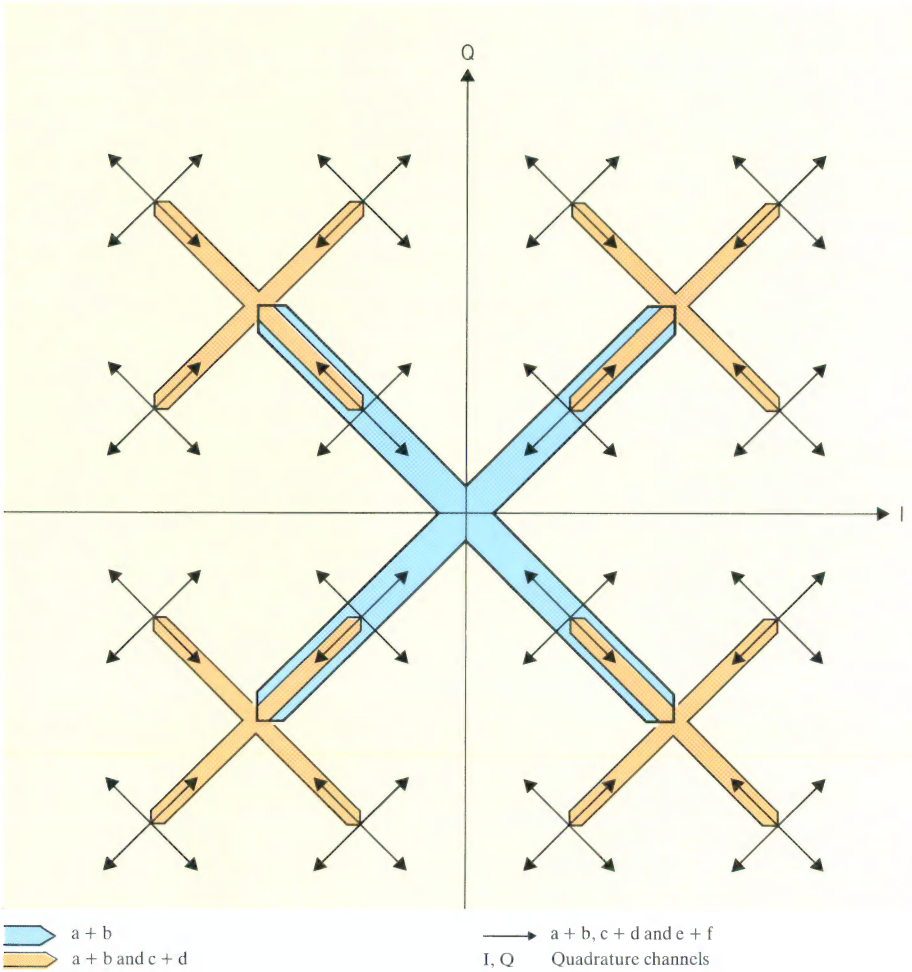


Fig. 4 Complex signal constellation for 4, 16 and 64 QAM

reduction remains effective in order to avoid jitter accumulating along a radio relay link. If there is no signal present at the input of a modulator set to the repeater station mode, the modulator switches automatically to the terminal station mode, forms the radio relay frame and transmits a scrambled alarm indication signal (AIS ≙ all ones). This provides a formally correct signal for the remainder of the link still in operation.

Demodulator (digital processing circuit and interface)

After coherent quadrature demodulation and (optional) adaptive equalization the baseband symbols are passed through the decision circuit, providing 2, 4 or 6 bits per symbol depending on the modulation format employed.

In the digital processing circuit of the demodulator inset (**Figs. 2, 3**), the bits are first differentially-or-Gray-decoded and converted to a serial data stream, D′, with associated timing signal, T′, (141.475 kbit/s).

These functions are combined with frame alignment in the differential decoder/aligner device (DGSYN). The descrambler/demultiplexer (DD) demultiplexes the service channel bits and the internal system information and passes them to the service channel demultiplexer (SCD) or the supervision circuit (SU) while the main data stream is descrambled. The CMI encoder, which is not required until the signal reaches the interface, is also incorporated in a gate array (DD). Bit rate conversion is again effected with the aid of the same BS and CTU integrated circuits employed in the digital processing circuit of the modulator. The BS and CTU circuits employing a narrowband phase-lock loop and 139-MHz VCXO similarly also provide for jitter suppression. This function is, however, only operational in the terminal station mode. It is disabled in the repeater station mode because a repeater station demodulator does not perform bit rate conversion and is always followed by a repeater station modulator with its jitter suppression.

Parity is monitored in the descrambler/demultiplexer of each demodulator but is not regenerated at repeater stations. This allows the quality not only of individual radio hops but also of an entire switching section to be supervised from the terminal station demodulator [8].

After CMI encoding (DD), an interface signal is produced in conformance with the pulse mask defined in CCITT Recommendation G.703 and is fed to a main output and a secondary output.

The compact, low-dissipation and reliable design of the signal processing functions described for the modulator and demodulator is due largely to semi-custom large-scale integration. This technique is also employed in the equalizer control circuit discussed below and in the carrier and timing recovery circuits [11, 12]. Its use also minimizes testing and trimming operations.

	4 QAM	16 QAM		64 QAM
Channel spacing	110 MHz	40 MHz	28 MHz	28 (29.65) MHz
Interleaved pattern	$\varrho = 0.5$	$\varrho = 0.5$	$\varrho = 0.5$	$\varrho = 0.45$
Cochannel	$\varrho = 0.5$	$\varrho = 0.19$	–	$\varrho = 0.25$

Table Roll-off factors for SAW filters depending on the modulation format and the channel allocation plan

Quadrature amplitude modulation and spectrum shaping

Quadrature modulation

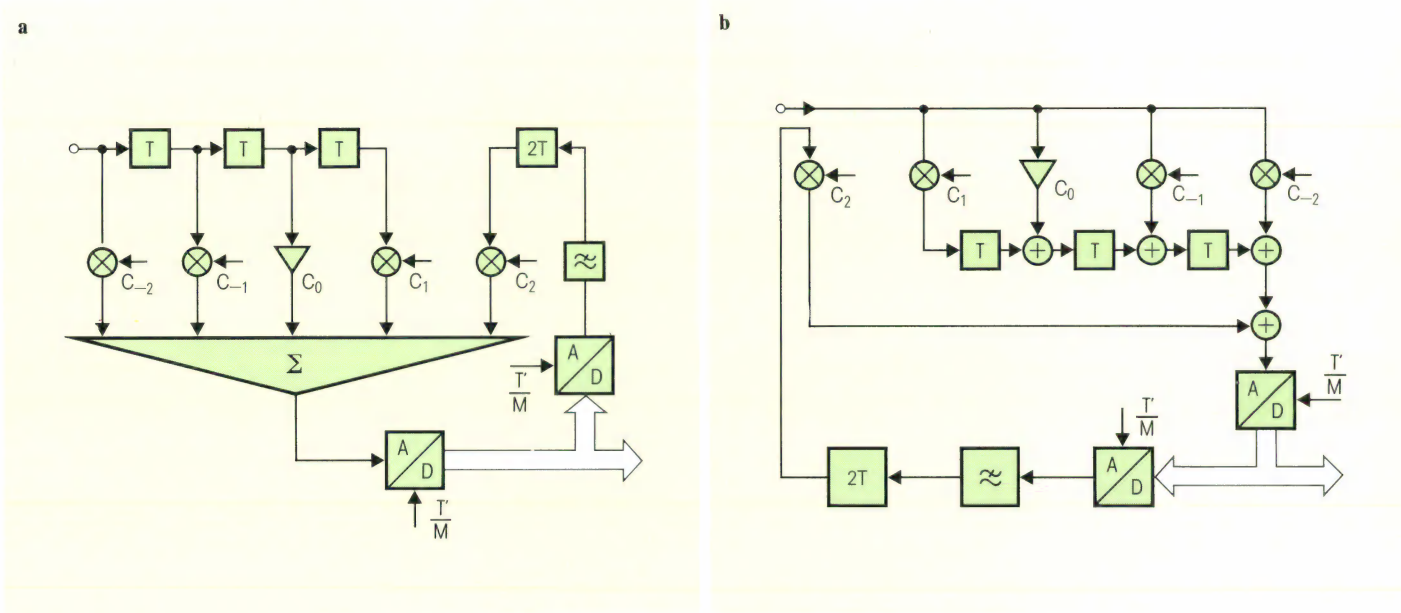
The purpose of the quadrature modulator (**Fig. 1**) is to represent each 2 (a,

Fig. 5 Transmit and receive SAW band-pass filters

b), 4 (a, b, c, d) or 6 (a, b, c, d, e, f) bit symbol as one of the corresponding 4, 16 or 64 states which the 140- or 70-MHz IF carrier is allowed to assume. This is illustrated in the complex signal plane for the complex envelope of the IF carrier in **Fig. 4.** The implementation adopted here is based on the weighted superposition of one, two or three 4-QAM signals (a+b), (a+b) and (c+d), or (a+b), (c+d) and (e+f). This facilitates the minimization of residual errors (e.g. unbalance) in the ring modulators employed. It is, however, only of benefit when employed in conjunction with the IF spectrum shaping described in the following section.

Spectrum shaping

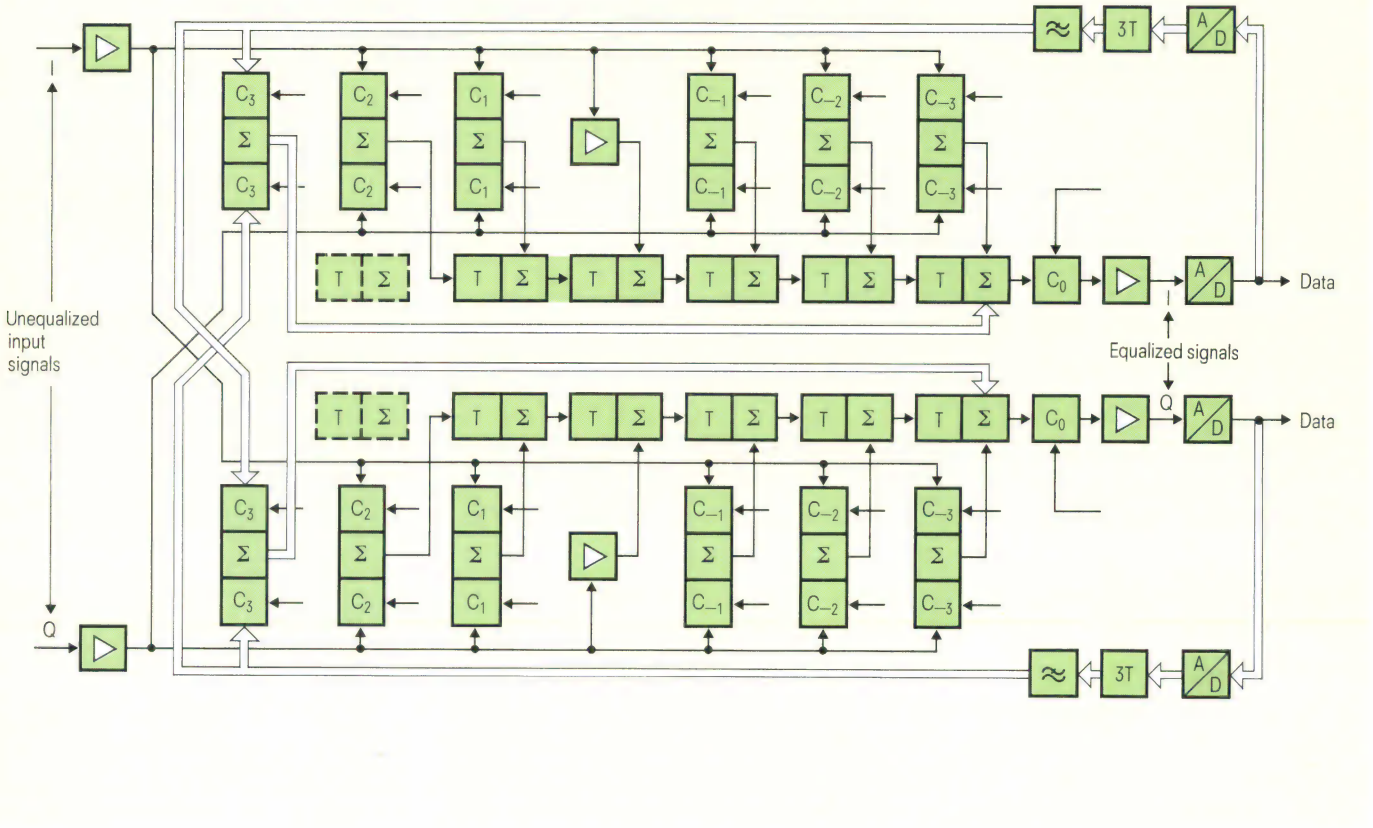
The pulse and spectrum-shaping filters can be implemented either as low-pass filters in the I and Q quadrature channels in the baseband of the QAM system or as band-pass filters at the intermediate frequency. This is another decision in which the available technology [14] is the crucial factor. The excellent characteristics of SAW technology enable the precise realization of filter functions. This enables freedom from intersymbol interference to be obtained in accordance with the Nyquist criterion [6] and permits interference-free adjacent channel operation, even with analog wideband systems for 1800 and 2700 voice channels.



C Coefficients T Delay element

Fig. 6 Equivalent realizations of an equalizer network with recursive coefficient

a Serial-in/parallel-out b Parallel-in/serial-out



C Coefficients I, Q Quadrature channels T Delay element

Fig. 7 Functional diagram of a complex equalizer with recursive coefficient

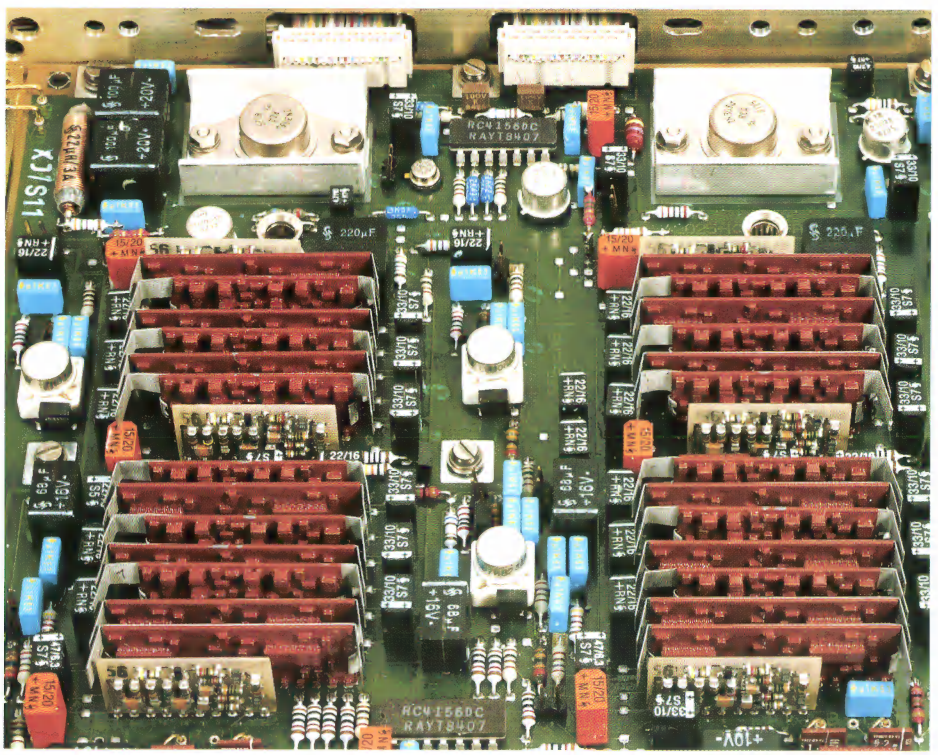


Fig. 8 Equalizer module

The filter partitioning between transmit and receive ends is optimum for the signal-to-noise ratio (matched filter) [7] and is also optimum for adjacent channel interference when the adjacent channels are identical. The transmit and receive SAW band-pass filters differ only in that the modulator filter incorporates equalization of the trapezoidal baseband pulses. The rise and fall times of these baseband pulses (about a quarter of the symbol duration) are important for minimizing foldover distortion [15]. The SAW filters are designed with various roll-off factors, depending on the channel allocation plan, the modulation format and the possible use of cochannel operation. Their roll-off factors are given in the **Table.** These SAW filters, unlike conventional LC filters, require no alignment and are much smaller in size, The pass-band attenuation inherent in these filters is equalized with the aid of hybrid integrated IF amplifiers.

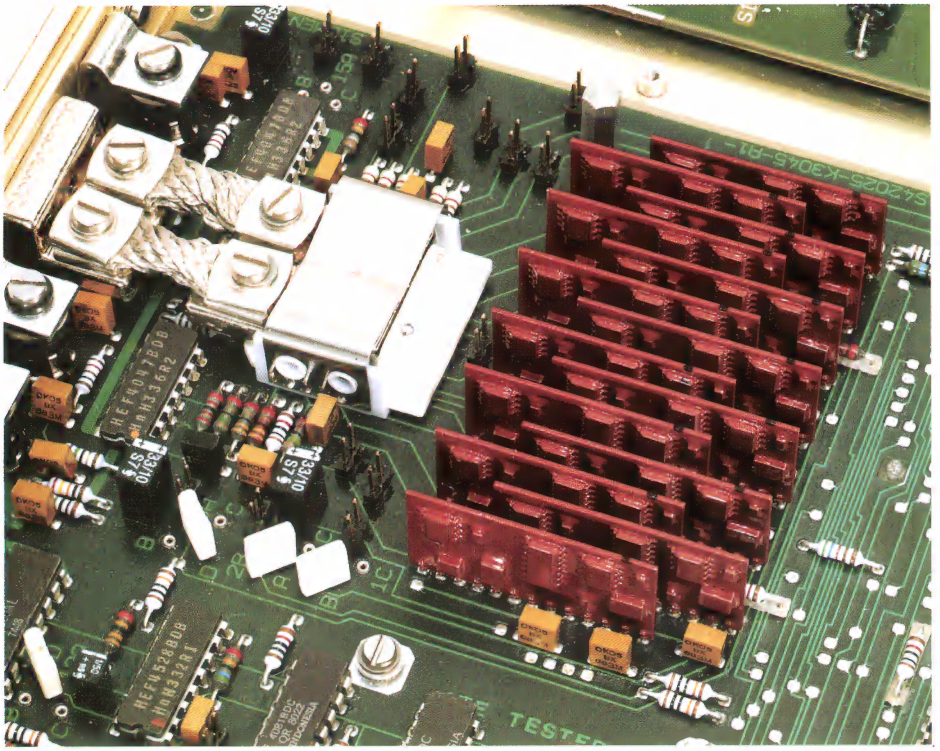


Fig. 9 Equalizer control module with CORR gate array and double integrator modules

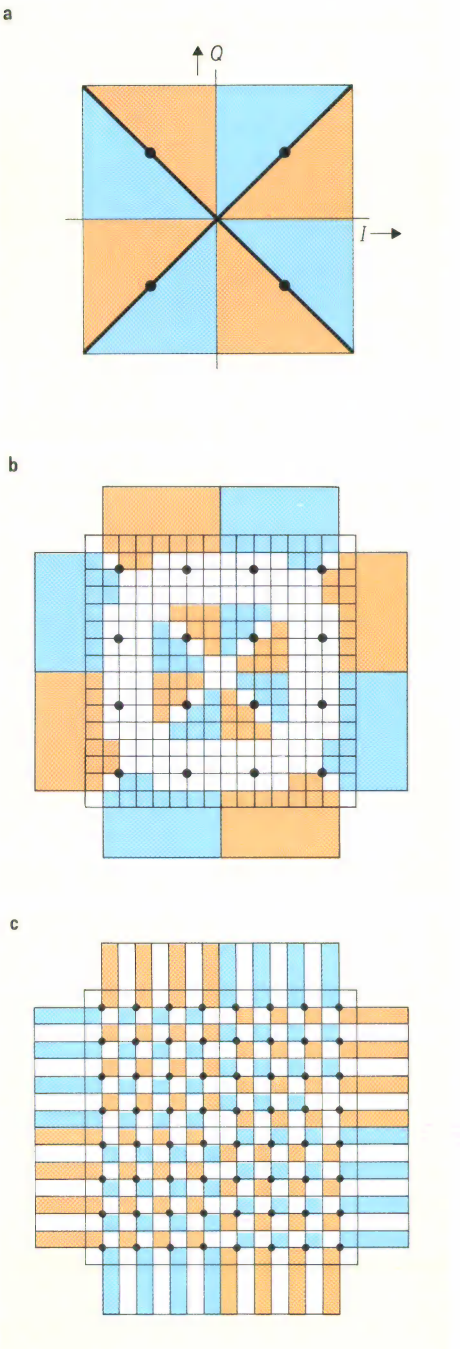


Fig. 10 QAM carrier recovery templates for 4 QAM (a), 16 QAM (b) and 64 QAM (c)

Fig. 5 shows the $\varrho = 0.5$ SAW band-pass filters employed in the DRM 140/140-16 modulator and demodulator insets.

Quadrature demodulation

The combined signal [2, 3] obtained via the main and diversity receivers is first amplified and the spectrum is shaped. Then coherent demodulation is performed (**Figs. 2, 3**) with the two orthogonal components of the recovered carrier signal. These quadrature carriers are furnished by a voltage-controlled oscillator (VCO) and a 90° phase shifter. Automatic control of the carrier phase minimizes the crosstalk between the I and Q channels and is described in more detail in the following sections. The demodulated n-level baseband signals are transferred to the adaptive equalizer or, if the demodulator has no equalizer, directly to the regeneration section (signal decision, carrier and timing recovery) (**Fig. 2**).

Adaptive time-domain equalizier (ATDE)

Owing to the special nature of the radio relay channel under multipath propagation conditions [16], a time-domain transversal equalizer with one additional recursive loop and coefficients set by the "zero-forcing" algorithm is the optimum compromise between performance and implementation cost [17, 18]. The basic considerations here are the equalizer's response to rapid changes in the channel response, i.e. its tracking capability, and the problems of realizing such a complex control system for 140-Mbit/s signals.

The equalization network itself consists of a complex transversal filter with one additional "far-off" recursive coefficient. Thus, the well-known advantages of a linear transversal equalizer and a decision feedback equalizer are merged, avoiding their specific shortcomings [9].

Complex equalizer network

The complex equalizer network is realized in the baseband of the QAM system as a time-continuous analog network. Although the number of real multipliers and delay elements is greater by a factor of 2 than for a theoretically equivalent IF solution, the baseband version is to be preferred. The reason for this is that it is easier to implement the analog modules in the baseband (less bandwidth, more favorable frequency range) and it is possible to compensate any unbalance introduced by the modem itself [19].

In order to make the overall architecture as modular as possible, the parallel-in/serial-out structure was adopted. This is shown for a real baseband channel in **Fig. 6** together with the more usual and theoretically equivalent serial-in/parallel-out arrangement. The equivalence shown still applies for complex filters. The functional breakdown into modules is shown in **Fig. 7.** Two double multipliers and two delay modules (both hybrid integrated circuits in thin-film

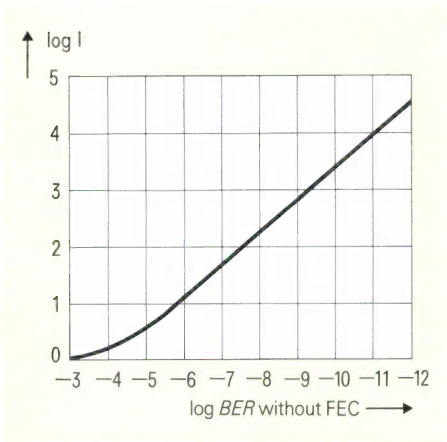


Fig. 11 Inprovement factor (I) of FEC versus the primary (uncorrected) *BER*

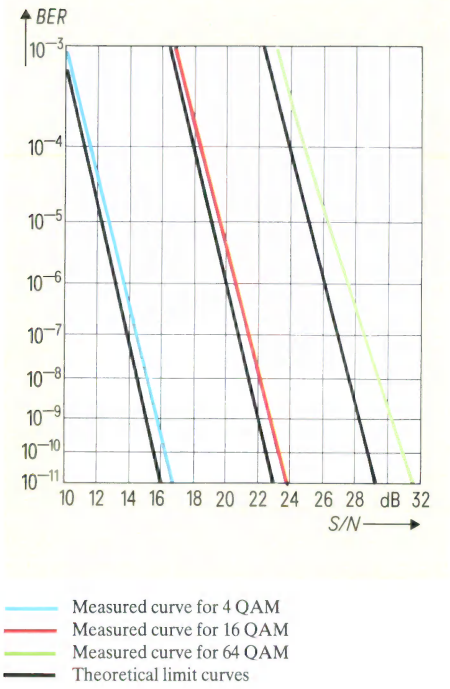


Fig. 12 Bit error ratio (*BER*) as a function of signal-to-noise ratio (*S/N*) for 4, 16 and 64 QAM

technology) form a complex tap. They can be cascaded to form a complex transversal filter of any order. The optimum compromise between performance and circuit complexity led to a version with seven taps (**Fig. 7**). **Fig. 8** shows an equalizer module with the many film-circuit modules. They are trimmed with the aid of a laser in order to obtain the necessary precision (frequency response of attenuation and delay as well as balance of the 4-quadrant coefficient multiplier). The center tap of the complex equalizer is real since the carrier recovery circuit with its template already provides for the optimum carrier phase during demodulation.

The signal decision circuit following the equalizer network (**Fig. 2**) incorporates monolithic integrated fast analog-digital converters, which make their data available to the equalizer control and carrier recovery circuits and to the previously discussed digital processing circuit of the demodulator inset. The converters obtain the timing signal required in the decision process from a VCO with a frequency-determining SAW device (141-MHz VCSO).

The VCSO is phase-locked to a reference signal that is derived from the threshold crossings of the baseband signals (4-QAM and 16-QAM without ATDE) or from the squared baseband signals (16-QAM with ATDE and 64-QAM). The important factor here is that both the carrier and timing recovery benefit from the performance of the equalizer.

Equalizer Control (Correlation)

For the particular situation of a radio relay channel subject to multipath propagation with few, but pronounced, indirect paths, the optimum approach to equalizer adaptation is by the zero-forcing algorithm [20]. This forces intersymbol interference (ISI) in the pulse response of channel and equalizer to be eliminated at the symbol timing instants within the span of the equalizer. The effect is that an equalizer network with seven complex coefficients reestablishes the regularly spaced zero crossings associated with a Nyquist pulse at three timing instants both before and after the mainlobe of the output pulse. The coefficient setting which meets this specification and corresponds in theory to the unique solution of a linear set of equations is obtained with the aid of a correlation unit. This unit monitors the dependence of the signal error at the sampling instant on previously and subsequently decided data and eliminates it on a time-averaging basis. The correlation operation is thus realized in two steps. First, the error and the signal are multiplied digitally, i.e. in the correlator gate array (CORR) with words 1-bit wide on a modulo 2 basis. Time averaging is then performed with thick-film double integrator modules (INT). An additional auto-zeroing facility, combining the advantages of gate array and hybrid film-circuit technology, is employed to keep circuit tolerances and temperature drift extremely low. This produces very precise correlation results which enable the equalizer to converge even under deep selective fading with the carrier recovery circuit not yet locked. This avoids outages being unduly prolonged by hysteresis between the system losing and regaining lock. The equalizer control module with CORR gate array (heat-sinked) and INT modules can be seen in **Fig. 9**. Any resetting required and the following

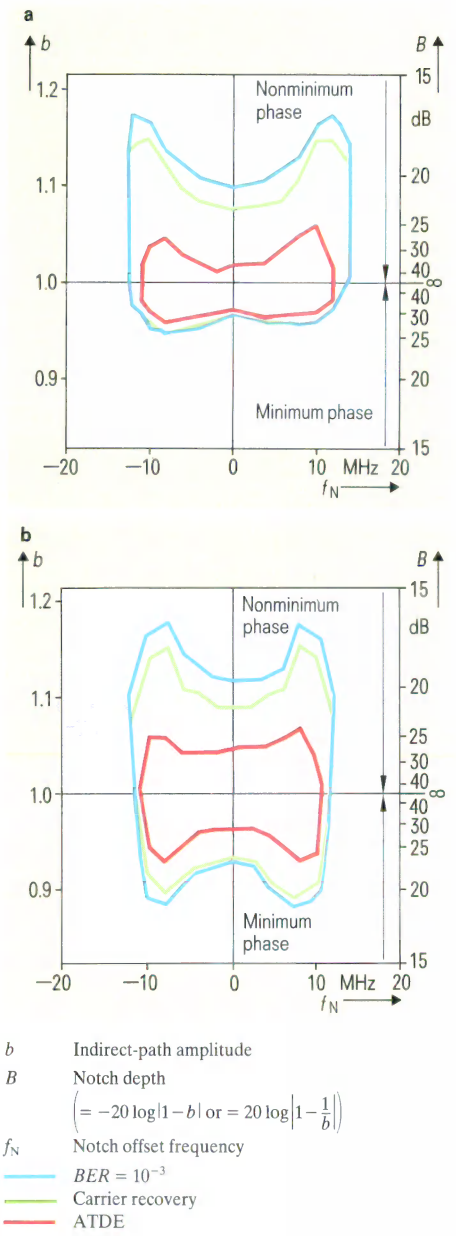


Fig. 13 Static signatures for regaining lock of ATDE, of carrier recovery for $BER = 10^{-3}$ for 16 QAM (a) and 64 QAM (b) (without IF slope equalizer)

tracking process are monitored and controlled by the acquisition unit (ACQ), which employs various criteria (e.g. coefficient setting voltages, loss of frame alignment, etc.).

Carrier recovery

In order to exploit the potential of quadrature amplitude modulation (QAM), the demodulation process must be coherent, i.e. employ a recovered carrier of correct phase as provided by the 140-MHz VCO in the quadrature demodulation [21]. The control voltage for this oscillator is derived with the aid of a digitally implemented template, which acts as a phase discriminator within the phase-locked loop. These templates are realized in the regenerator gate array, REG, (**Fig. 2,** 4- and 16-QAM) or in the carrier and timing recovery gate array (CTR). **Fig. 10** shows these templates for 4-, 16- and 64-QAM signal constellations.

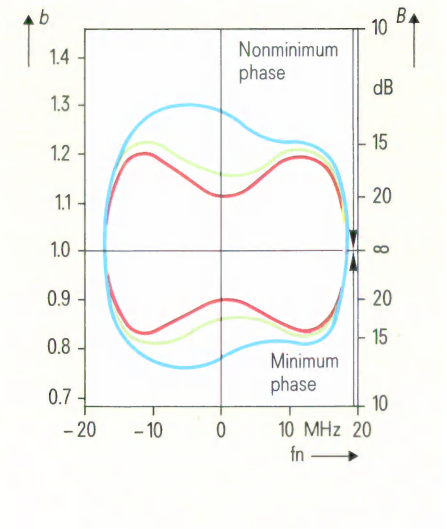
If the QAM signal constellation rotates relative to the template, the four outer and the four inner symbols will all lie either in "red" or "blue" fields and will thus supply a positive or negative contribution to the control voltage. Symbols located in "white," neutral fields do not contribute to the control process.

Since the equalizer control circuit furnishes useful coefficient setting voltages even while the carrier oscillator (140- or 70-MHz VCO) is searching for lock, the performance of the equalizer is fully exploited in locking the carrier recovery circuit. This provides the low hysteresis between the carrier recovery loop losing and regaining lock.

The use of modern semi-custom integrated circuits in both this and the other section of the modem is again a crucial factor in making the realization of these concepts at all possible.

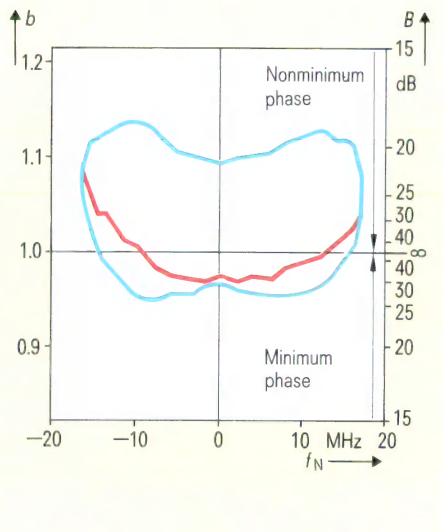
Frequency-domain equalizer

Most QAM digital radio systems employ frequency-domain equalization in the form of simple slope (and possibly bump) equalization of the received signal amplitude spectrum [2]. Since this type of equalization, which is applied either in conjunction with ATDE or without, does not necessarily require demodulated signals, it can be incorporated in the radio receiver [2] or in the demodulator. **Fig. 3** shows that the 64-QAM demodulator incorporates such a simple slope equalizer realized at IF. The equalizer network is a simple transversal filter [19]. The control voltage for the slope adjustment is conveniently derived from a combination of the baseband signals.



b Indirect-path amplitude
B Notch depth
$\left(= -20 \log|1-b| \text{ or } = 20 \log\left|1-\frac{1}{b}\right|\right)$
f_N Notch offset frequency
Sweep rate 300 MHz/s
Sweep rate 1500 MHz/s
Sweep rate 5000 MHz/s

Fig. 14 Dynamic signature of 16 QAM demodulator with ATDE with seven complex coefficients (indirect-path delay 6.3 ns; sweep range ± 2.5 MHz)



b Indirect-path amplitude
f_N Notch offset frequency
B Notch depth
$\left(= -20 \log|1-b| \text{ or } = 20 \log\left|1-\frac{1}{b}\right|\right)$
With additional IF slope equalizer
Without additional IF slope equalizer

Fig. 15 Static signature for $BER = 10^{-3}$ for 16 QAM

Forward error correction

A simple technique of forward error correction (FEC) is incorporated in the 64-QAM demodulator making use of already available signals such as the parity check bit and so-called "soft information" on each symbol employing extra bits provided by the A/D converter. This simple block code based on "soft decisions" does not require additional redundancy to be incorporated in the symbol sequence. Therefore no modifications are necessary in the transmitter/modulator. **Fig. 11** shows the performance of this decoding scheme in the presence of additive white Gaussian noise (AWGN) by linking the *BER* before correction and the improvement factor of the FEC.

In spite of its simplicity, this FEC performs very well at a low primary *BER*, and the $(N+1)$ protection switching equipment can be activated before any bit error in the corrected output data occurs [8].

System characteristics

The digital radio modem equipment naturally meets all the interface conditions specified in CCITT Recommendation G.703 (e.g. jitter tolerance, cable attenuation equalization, reflection coefficients, frequency tolerance, etc.). Its performance is also characterized in particular by the system curve (*BER* as a function of the signal-to-noise ratio, *S/N*) and the signature. **Fig. 12** shows the typical system curves measured with the modems connected in a loop. The resultant degradation relative to the expected theoretical curve is very small. The signal and noise powers on which this is based were both measured after the receive spectrum-shaping filters.

Measurement of the system signature [16] is based on a two-path model of the radio relay channel with, for instance, a

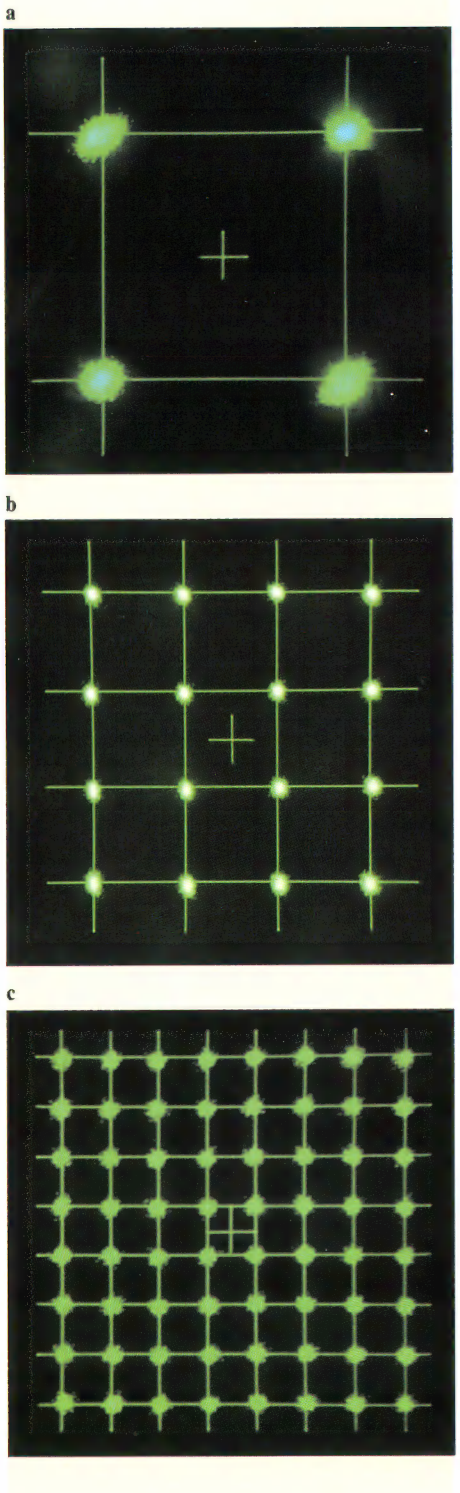


Fig. 16 QAM signal constellations for 4 QAM (a), 16 QAM (b) and 64 QAM (c) measured in real time mode and displayed on the screen of a modern test equipment (constellation display)

6.3-ns indirect-path delay [22] and indicates the resistance of the system to propagation-related linear distortion.

Fig. 13 shows at which notch depth/notch offset frequency pairs the equalizer regains lock, the carrier recovery regains lock and the *BER* falls below 10^{-3} for the 16- and 64-QAM modems. Since the first two signatures are well within the last one, the excellent acquisition performance and absence of any hysteresis in the $BER = 10^{-3}$ signature is demonstrated. In addition, the superior performance with respect to minimum phase fading ($b<1$) due to the "far-off" quantized recursion is shown.

Since these measured curves describe the performance of the equalizer only under static channel conditions, what is known as the dynamic signature was introduced [17]. This involves the notch frequency of the two-path channel being varied dynamically (swept) to test the ability of the equalizer to adapt to the rapidly changing channel situations. The sweep range was chosen to be large enough (± 2.5 MHz) to cause a large change in coefficients. As well as the $BER = 10^{-3}$, it is necessary to state the sweep rate for each signature curve as an additional parameter. **Fig. 14** shows for the 16-QAM modem that significant degradation only occurs at sweep rates greater than 1000 MHz/s. This is significantly above the rate of change observed on radio hops. Additional improvement in the signature is provided by the IF amplitude equalizer integrated in the radio receiver [2] (**Fig. 15**).

Supervision and test outputs

Circuit and equipment disturbances are for the most part detected separately. Both result in transmission of a remote supervision signal (isolated contact) and a signal (electronic contact) to the control logic of the $(N+1)$ protection switching equipment [8].

In addition to the secondary baseband and IF outputs, there are outputs on the front panel of the demodulator inset for the error pulse derived from parity violations as well as for the demodulated and equalized baseband signals with the associated timing. With the aid of modern test equipment it is thus possible to display the signal constellations (**Fig. 16**) which, similar to the eye diagram, provide a ready means of assessing the performance of the equipment. The demodulator incorporating an equalizer also enables the coefficient setting voltages to be detected and recorded during operation. This provides an indication of the channel response and is thus a valuable tool in the hands of the system operator for evaluating the radio hops.

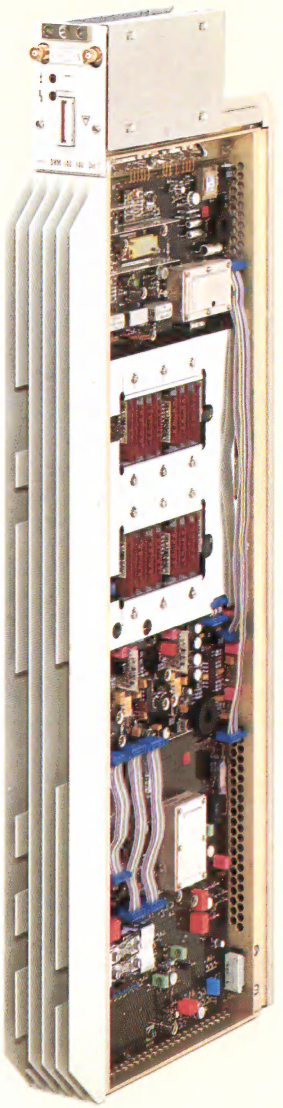


Fig. 17 16-QAM demodulator inset with ATDE

Mechanical design

The modulator and demodulator are designed as vertically divided plug-in insets, each measuring 700 mm high and 54 mm wide, for mounting in style 7R racks (inset type III) [23]. **Fig. 17** illustrates the design of the 16-QAM demodulator inset incorporating an adaptive equalizer. The 100-mm head of these insets incorporates the "supervision" module. In order to keep the operating temperature as low as possible, the one-

piece front panels are provided with cooling fins for improved heat removal. In addition, the principal sources of heat in the modules (e.g. gate arrays) are connected to the front panel via a thermal conductor. Coaxial connectors on the front panel link the inset via the inset housing to the station cabling. A test meter located centrally in the radio relay system can be connected via a multiple connector. Connector strips on the rear of the insets establish the connections to the radio relay units, the protection switching units and the station wiring.
If the demodulator is intended for use in cochannel operation, a second head is attached at the other end of the inset. This second head contains all the necessary connections (**Fig. 3**) to and from the XPIC [4]. It can be retrofitted to each demodulator without any soldering, because the corresponding printed circuit boards already incorporate the necessary interfaces.

Outlook

The modern technology employed in the 4/16/64 QAM digital radio modems (SAW devices, semi-custom monolithic and hybrid integrated circuits) and the adaptive devices provide a firm foundation for further advances toward new generations of systems employing higher level modulation methods. In particular, those functions which are currently realized in analog form will be implemented in the future with the aid of VLSI technology, processing signals discrete in time and amplitude, in other words, digitally. The increasing importance thus assumed by digital processing means that further development will be required to optimize the algorithms and their implementation in monolithic integrated form. Thus, the synthesis of algorithm and circuit development with the technology employed for their implementation has become more than ever the basis of future-oriented, modern systems.

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Berthold Lankl, Josef Nossek and Georg Sebald

Cross-Polarization Interference Canceller for Multilevel QAM Digital Radio Relay Systems

In high-capacity, long-haul and medium-haul digital radio systems the available frequency band is usually shared among the channels by using an interleaved pattern. This implies that adjacent channels have orthogonal polarizations in order to reduce the adjacent channel interference by cross-polarization discrimination (XPD).

Simply using both orthogonal polarizations of one RF carrier frequency simultaneously (cochannel operation) results in an improvement of the bandwidth efficiency by a factor of two, regardless of the number of modulation levels already employed.

To reduce the increased vulnerability of these systems to cross-polarization interference effects, a cross-polarization interference canceller (XPIC) is necessary at least in multilevel QAM systems operating under unfavorable propagation conditions.

Introduction

In QAM digital radio systems the bandwidth efficiency has been improved by increasing the number of modulation levels from system generation to system generation.

Squaring the number of levels results in a doubling of the number of bits/second transmitted within the same bandwidth. This can easily be realized starting from 4 QAM going to 16 QAM. The step from 16 to 256 QAM is now under development and will necessitate major efforts to achieve the desired performance; but an additional doubling would lead to 65,536 QAM (!) which at least today seems to be purely academic. Therefore it makes sense to look at other possibilities for increasing the bandwidth efficiency. One very attractive way is cochannel operation, which makes use of the two orthogonal polari-

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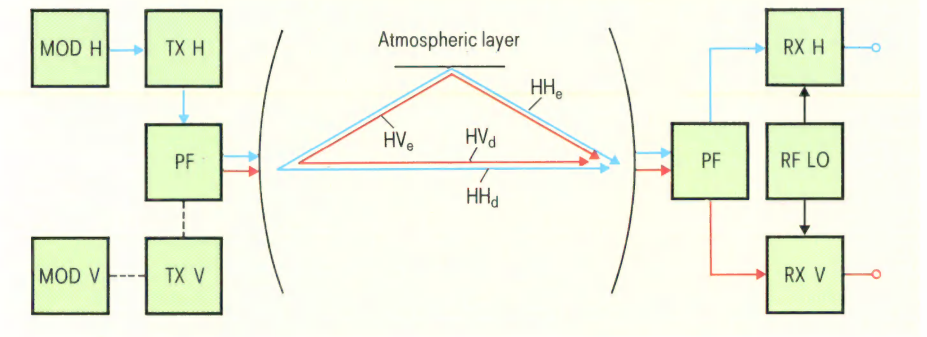
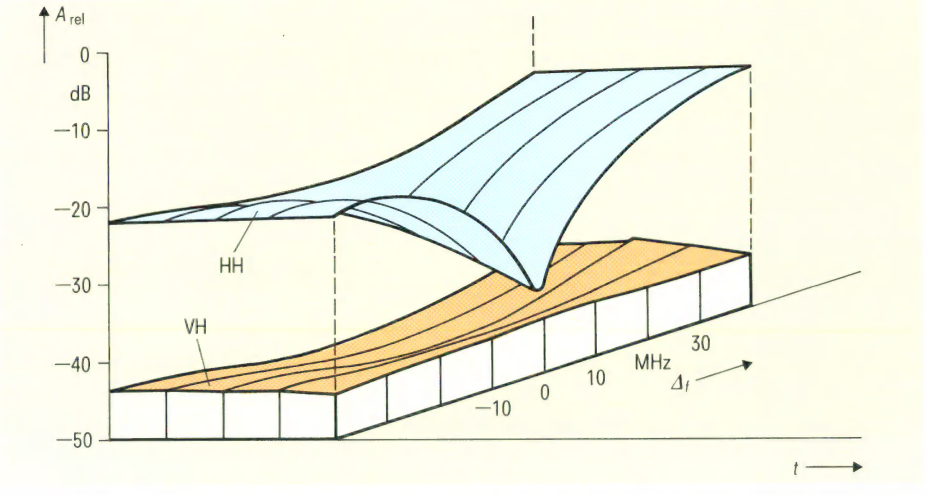


HH_d	Direct signal from horizontal transmitter to horizontal receiver	MOD H	Modulator for horizontal polarization
HH_e	Echo signal due to atmospheric layer from horizontal transmitter to horizontal receiver	MOD V	Modulator for vertical polarization
HV_d	Direct signal from horizontal transmitter to vertical receiver	PF	Polarization filter
HV_e	Echo signal due to atmospheric layer from horizontal transmitter to vertical receiver	RF LO	Radio frequency local oscillator
		RX H	Receiver for horizontal polarization
		RX V	Receiver for vertical polarization
		TX H	Transmitter for horizontal polarization
		TX V	Transmitter for vertical polarization

Fig. 1 Transmission paths for cochannel operation during multipath propagation



A_{rel}	Relative attenuation	VH	Signal from vertical transmitter to horizontal receiver
HH	Signal from horizontal transmitter to horizontal receiver		

Fig. 2 Time-variant nature of the transmission paths

zations available at the same carrier frequency. It results in doubled channel capacity within the same bandwidth without increasing the number of modulation levels [1]. Cochannel operation with high-level modulation schemes requires very high cross-polarization discrimination (XPD). Modern radio relay antennas [2] meet the XPD requirements at least under ideal propagation conditions; nevertheless cross-polarization interference (XPI) between nominally orthogonally arranged channels can occur under various conditions, e.g. rainfall, multipath propagation and equipment imperfections [3]. Additional means for enhancing the cross-polarization discrimination are therefore necessary. Since the interference effects are time-variant, the countermeasure applied must be adaptive.

Such adaptive cross-polarization interference cancellers (XPICs) should fit optionally into the structure of the existing radio equipment. This means first of all that the XPICs have to operate on the two plesiochronous data signals being transmitted in the two orthogonal polarization directions. There is thus no need for any overhead information for justification and synchronization of the two signals, with a consequent increase in the gross bit rate.

This is advantageous especially in the case of 16-QAM systems operating with the 40-MHz channel spacing available in the RF bands at 3.9 GHz, 4.7 GHz, 6.7 and 11.2 GHz.

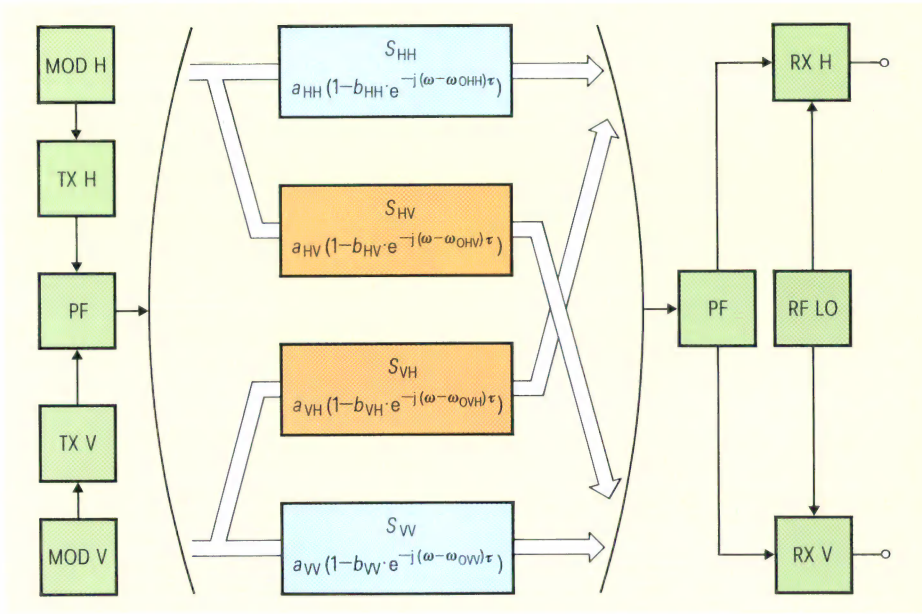
The XPIC presented here fulfills the requirements stated above by using a fractionally-spaced transversal filter which offers superior cancellation performance, especially if the data signals are plesiochronous.

Channel model

The main reasons for XPI in radio systems are:

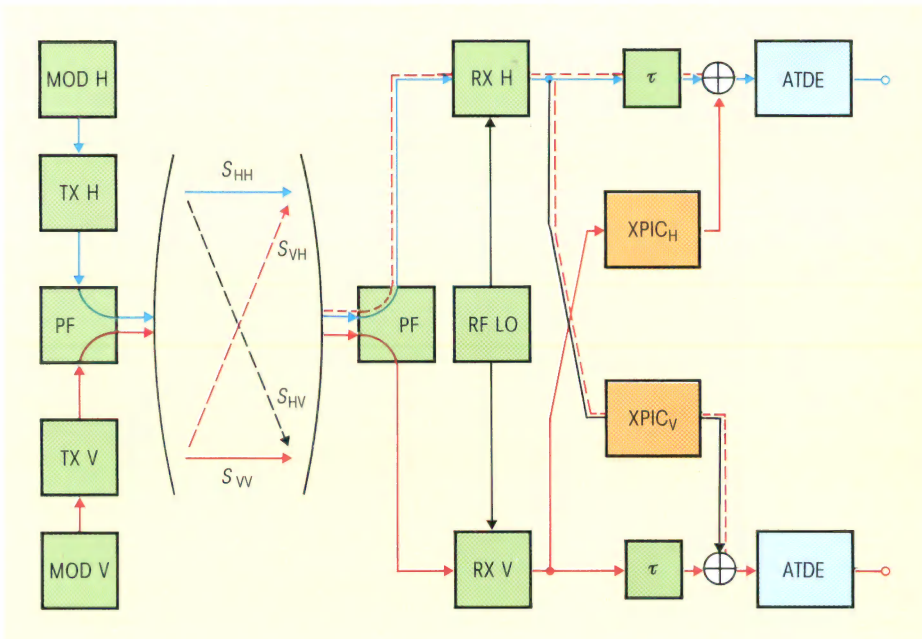
- non-dispersive depolarization (due to rain, snow), especially in RF bands above 10 GHz,
- dispersive depolarization due to multipath propagation, especially in RF bands below 10 GHz,
- equipment imperfections.

Reduction of the XPD encountered during multipath propagation is depicted in **Fig. 1**. Since these dispersive effects are



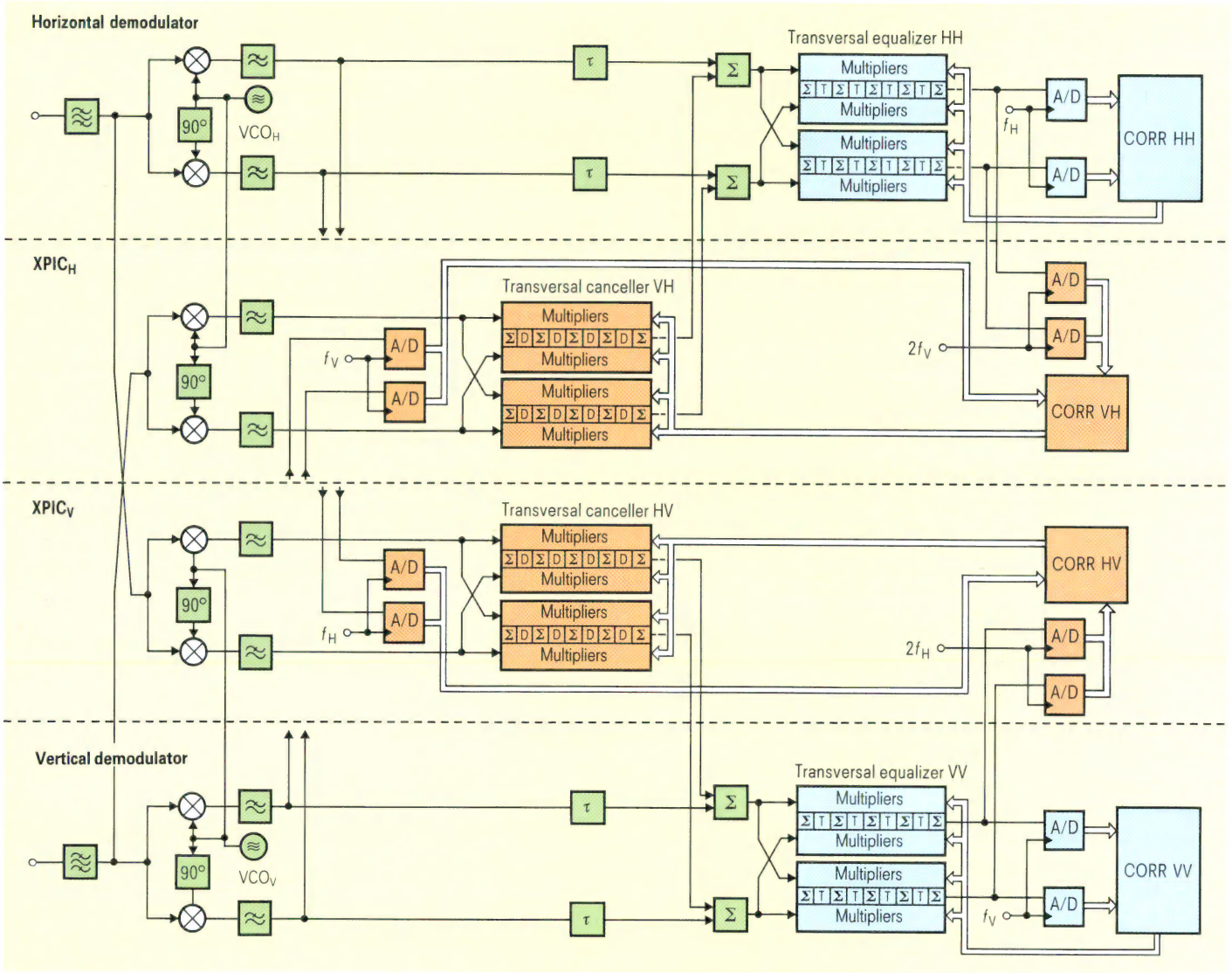
MOD H	Modulator for horizontal polarization	S_{HV}	Transfer function from horizontal transmitter to vertical receiver
MOD V	Modulator for vertical polarization	S_{VH}	Transfer function from vertical transmitter to horizontal receiver
PF	Polarization filter	S_{VV}	Transfer function from vertical transmitter to vertical receiver
RF LO	Radio frequency local oscillator	TX H	Transmitter for horizontal polarization
RX H	Receiver for horizontal polarization	TX V	Transmitter for vertical polarization
RX V	Receiver for vertical polarization		
S_{HH}	Transfer function from horizontal transmitter to horizontal receiver		

Fig. 3 Channel model for cochannel operation



ATDE	Adaptive time-domain equalizer	S_{VH}	Transfer function from vertical transmitter to horizontal receiver
MOD H	Modulator for horizontal polarization	S_{VV}	Transfer function from vertical transmitter to vertical receiver
MOD V	Modulator for vertical polarization	TX H	Transmitter for horizontal polarization
PF	Polarization filter	TX V	Transmitter for vertical polarization
RF LO	Radio frequency local oscillator	τ	Delay element
RX H	Receiver for horizontal polarization	$XPIC_H$	Cross-polarization interference canceller for horizontal polarization
RX V	Receiver for vertical polarization	$XPIC_V$	Cross-polarization interference canceller for vertical polarization
S_{HH}	Transfer function from horizontal transmitter to horizontal receiver		
S_{HV}	Transfer function from horizontal transmitter to vertical receiver		

Fig. 4 Cancellation principle of a cochannel transmission system



A/D	Analog to digital converter	D	Delay element (1/2 symbol period)	VCO_V	Carrier recovery oscillator of vertical demodulator
$CORR_{HH}$	Correlation unit for adaptation of the transversal equalizer of the horizontal demodulator	f_H	Clock frequency of the horizontal demodulator	$XPIC_H$	Cross-polarization interference canceller for horizontal polarization
$CORR_{HV}$	Correlation unit for adaptation of the transversal canceller of the $XPIC_V$	f_V	Clock frequency of the vertical demodulator	$XPIC_V$	Cross-polarization interference canceller for vertical polarization
$CORR_{VH}$	Correlation unit for adaptation of the transversal canceller of the $XPIC_H$	$2f_H$	Double clock frequency of the horizontal demodulator	τ	Delay unit
$CORR_{VV}$	Correlation unit for adaptation of the transversal equalizer of the vertical demodulator	$2f_V$	Double clock frequency of the vertical demodulator	Σ	Summation amplifier
		VCO_H	Carrier recovery oscillator of horizontal demodulator	T	Delay element (1 symbol period)

Fig. 5 Configuration of complete signal processing with adaptive time domain equalization and cross-polarization interference cancellation

most difficult to combat, they are of principal concern for the canceller concept.

Let us assume that only the horizontal polarization on the transmit side is used. The blue lines (HH_d, HH_e) show the transmission paths from the transmit to the receive antenna for horizontal polarization. But there are also paths to the receiver cross-coupling the ideally orthogonal polarizations, shown in red lines (HV_d, HV_e). HV_d incorporates static contributions due to equipment imperfections which are also present under ideal propagation conditions. HV_e is present only under multipath conditions and results in a transfer function, S_{HV}, which is different from S_{HH} because the signal, HV_d, contains different contributions.

Fig. 2 shows the time-variant nature of these transmission paths. It is obvious that during deep selective fading the input power at the receiver for horizontal polarization (HH) is severely decreased, while the interfering power is not correlated and remains approximately constant. These phenomena are well known [4, 5].

If the above mechanisms responsible for the reduction in the cross-polarization discrimination (XPD) are taken into account, modeling of the transmission channel for cochannel operation can be performed by assuming four transfer functions (S_{HH}, S_{HV}, S_{VH}, S_{VV}) [6]. Each transfer function is described by a simple three path model shown in **Fig. 3** [7]:

$$S(\omega) = a\,[1 - b \exp(-j\,(\omega - \omega_o)\,\tau]$$

This model takes into account linear distortion of the "in-rail" transmission paths (S_{VV}, S_{HH}) causing intersymbol interference (ISI) and cross-polarization

interference (XPI) via the "cross-rail paths" (S_{VH}, S_{HV}). Both effects contribute to the degradation of the eye pattern and, therefore, to an increased bit error ratio. The ISI can be reduced by adaptive equalization and the XPI by adaptive cancellation.

Canceller concept

Fig. 4 shows the channel model and the corresponding principal arrangement of a cochannel transmission system including XPICs and adaptive time-domain equalizers (ATDE).

The transmitted signal in the horizontal channel (blue) is disturbed by the vertical signal (red, broken) on the receive side via the "cross-rail" path, S_{VH}. The basic idea for cancellation is to add a compensation signal (red, solid), which is derived from the vertical receiver and finally processed in the $XPIC_H$. In order to ensure that the compensating (red, solid) and the interfering signal (red, broken) cancel each other, no frequency offset between the local oscillators of the RF down-converters is permissible. To ensure that the compensating and interfering signals are not time-shifted, the signal delay of the XPICs must be compensated by delay elements (τ) corresponding to the nominal delay of the canceller filter.

At the summation point the XPI is considerably reduced. The remaining ISI, caused by the linear distortion of the S_{HH} path, must be removed with the aid of adaptive time-domain equalizers (ATDE) [8].

Since the type of linear distortion in the "in-rail" and the contamination by the "cross-rail" paths of the channel are very similar, the signal processing in the canceller is similar to that in the ATDE.

One important design objective of the XPIC was to make use of technologies and techniques which were successfully employed in the ATDE [8]. This leads to a baseband implementation of the canceller. **Fig. 5** shows the actual realization of the complete signal processing of the adaptive equalization and the cross-polarization interference cancellation. The integration of the individual processing units into the different insets (demodulators, XPICs) is also depicted. The concept of carrier and clock recovery in the demodulators is unchanged

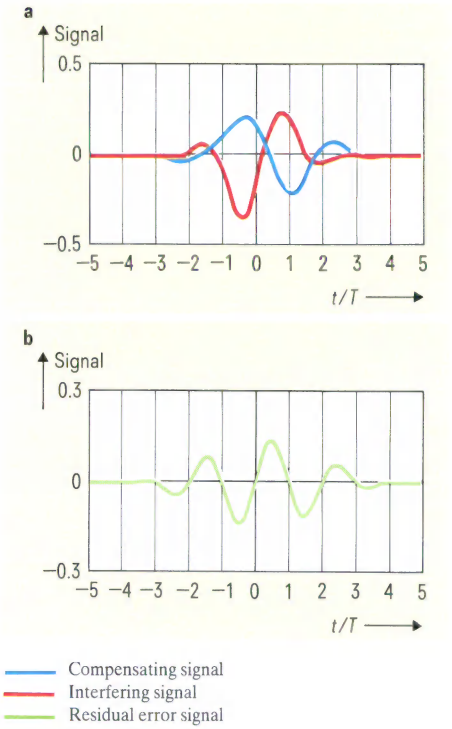


Fig. 6 Interfering and compensating signal of the baud-spaced 5-tap canceller (a) and residual error signal after cancellation (b)

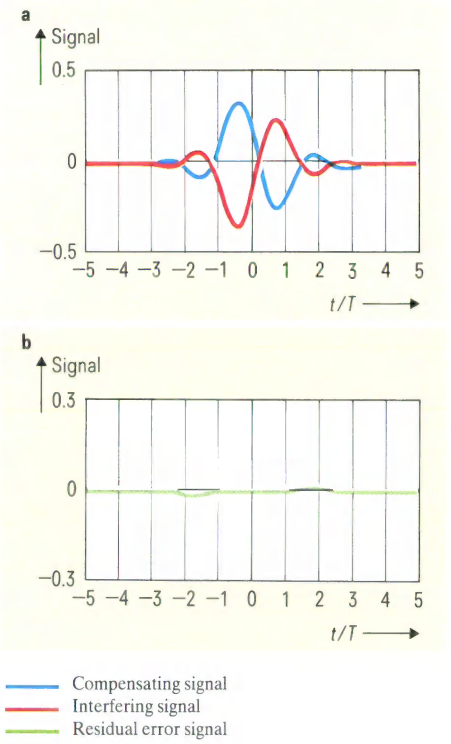


Fig. 7 Interfering and compensating signal of a fractionally-spaced (T/2) 5-tap canceller (a) and the residual error signal after cancellation (b)

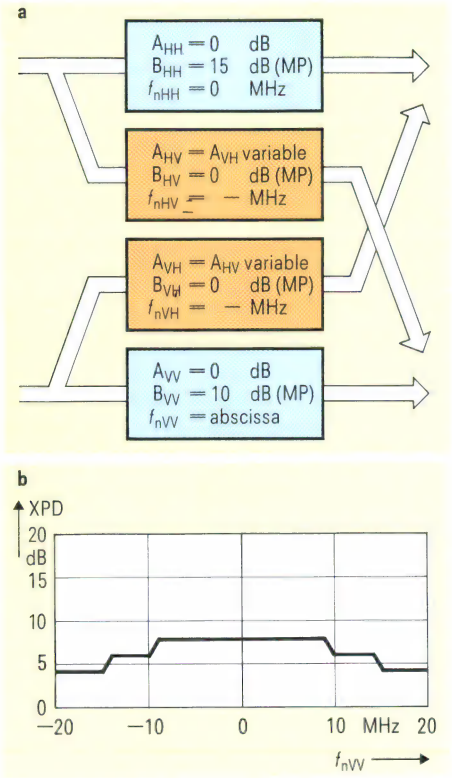
[9]; the clock and carrier signals are provided for use in the XPICs.

In order to ensure that the compensating signal and the signal to be compensated (interfering) have no frequency offset, the IF signal used for the generation of the cancellation signal is demodulated with the same IF carrier as used for demodulation of the wanted, but contaminated, signal.

As already mentioned, the XPICs have to operate with plesiochronous data signals, which leads to permanent changes in the relative timing of the interfering signal with respect to the wanted signal. Obviously, the tap settings of the canceller filters should not change as long as the channel transfer functions (**Fig. 3**) are constant. Since the control voltages for the transversal filters are generated by processing sampled signals, it is quite obvious that these control voltages depend on the actual sampling instants. Therefore, sampling is always carried out with the clock of the interfering signal, not the wanted signal, to provide the canceller control voltages.

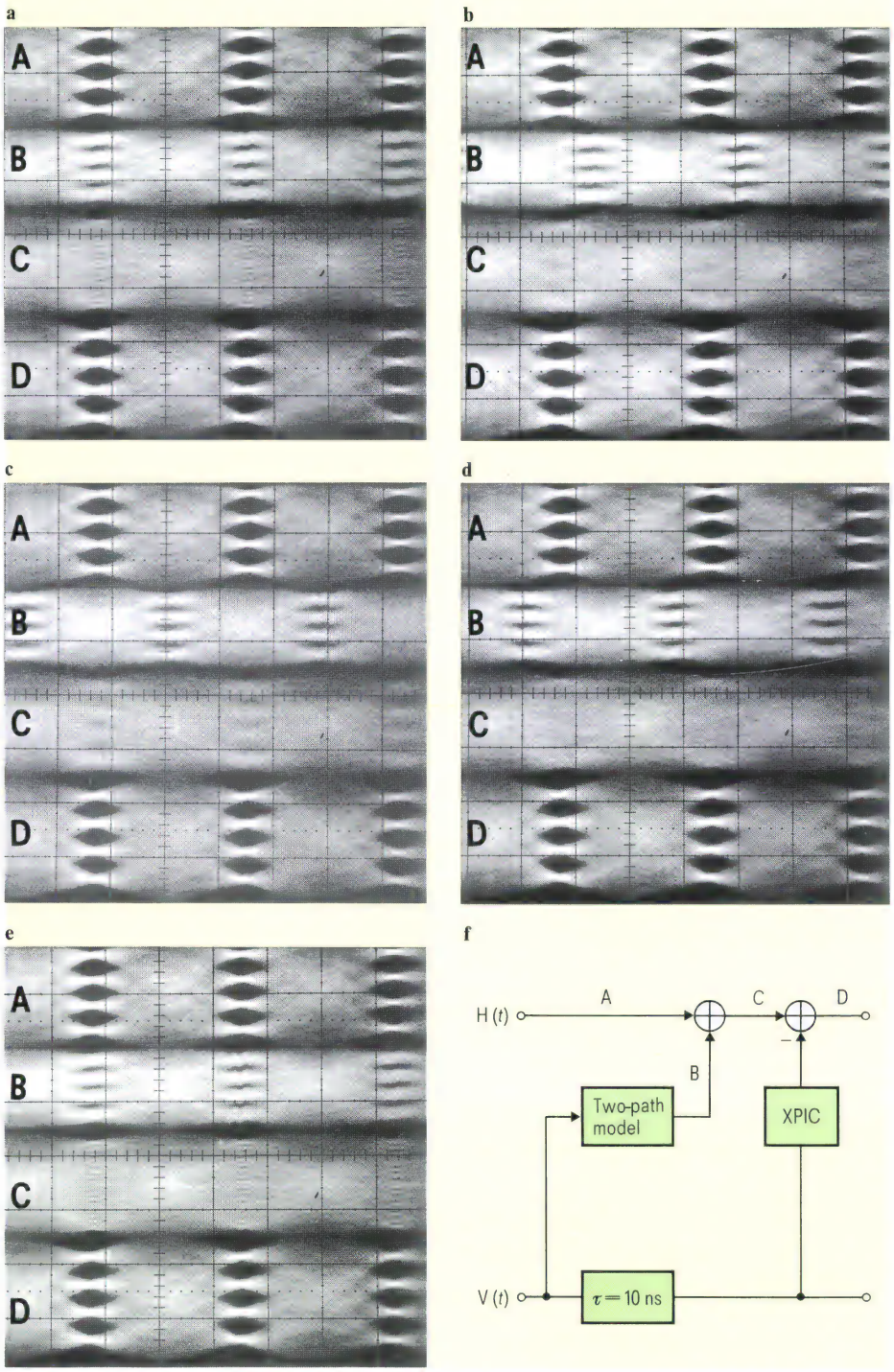
The performance of a baud-spaced canceller filter is demonstrated for a 20-dB center notch in the "cross-rail" path, VH, and flat fading in the two "in-rail" paths, VV and HH. **Fig. 6a** shows the interfering (red) and compensating (blue) signals for a baud-spaced 5-tap canceller filter. **Fig. 6b** shows the residual error signal, which is almost zero at the timing instants, but relatively large in between. However, due to the plesiochronous operation, the sampling instants of the wanted signal will not normally coincide with the above mentioned zeros in the residual error signal. This shows that simply adapting equalizer concepts for the implementation of a canceller does not lead to a satisfactory solution. Consequently, in the actual XPIC realization a fractionally-spaced canceller filter is used in order to overcome this drawback. The results obtained with this type of filter are shown in **Fig. 7a, b** for the same channel situation and the same number of multipliers as before.

The basic reason for the clearly superior performance of the fractionally-spaced transversal filter compared to the baud-spaced filter stems from the coincidence of the interference and the cancellation signals enforced at fractionally-spaced timing instants. The coincidence of the two signals at timing instants now obeying the sampling theorem leads to a coincidence at any time. As a result, the



A_{xy} Flat fading attenuation
B_{xy} Notch depth (Rummler model)
f_{nxy} Notch frequency
MP Minimum phase
XPD Cross-polarization discrimination

Fig. 8 Typical channel model (a) and the performance of the chosen canceller/equalizer structure (b)



A Undisturbed transmitted signal with horizontal polarization
B Interfering signal from vertical transmitter to horizontal receiver
C Disturbed received signal with horizontal polarization
D Reestablished horizontal signal after cancellation

Fig. 9 Actual oscillograms of the measurement of signal cancellation with 5-tap fractionally spaced transversal filter with a timing difference of 0° (a), 90° (b), 180° (c), 270° (d), 360° (e), and the setup of the measurement (f)

cancellation process is insensitive to changes in the relative timing of both plesiochronous signals.

The realized structure with a preceding canceller and a subsequent equalizer offers the best compromise for the most relevant multipath channel situations [9].

The evaluation of the XPIC performance is a rather complex task because of the large number of variable parameters in the channel model. A basic assumption for evaluating the performance of the canceller/equalizer concept is the simultaneous presence of ISI and XPI.

As an example, the performance of the chosen canceller/equalizer structure for typical channel model parameters is shown in **Fig. 8**. The diagram shows the permissible XPD for 100% eye closure in the horizontal receiver versus the offset frequency of a 10-dB notch in the VV path (**Fig. 8b**). In the HH path a fixed multipath situation is assumed which causes an eye closure due to ISI of 50% after equalization. One can see that the permissible XPD could be 10 dB or less for an eye closure of 100%. Numerous similar simulations have been performed to make sure that the chosen concept performs well under all relevant channel situations.

Realization

In order to ensure a highly modular overall DRS 140/... radio system, the XPICs are retrofitted as options. For instance, a radio system configuration for cochannel operation should be first

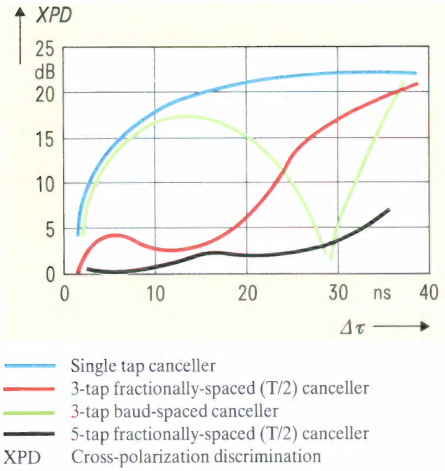


Fig. 10 Comparison of baud-spaced and fractionally-spaced filters showing the sensitivity to delay differences on the receive side

tried without XPICs. Only if required by the properties of the particular hop will the XPICs be installed without modifying the existing rack layout. Provision must be made in the demodulators and the receivers for this purpose, but this provision is of a rather simple nature. The need for modularity also emphasizes the need for the XPICs to be able to process the plesiochronous data signals.

A normal configuration for cochannel operation which suffers from XPI problems requires two XPIC insets (**Fig. 5**). The insets are identical and can be inserted into the rack without disturbing the hot data traffic. As is evident from **Fig. 5**, only few interconnections between the demodulators and XPICs are necessary, but it is important that the cable lengths are short and matched for every setup. The four insets (two demodulators, two XPICs) are, therefore, arranged close together, but the complete demodulator-XPIC arrangement can be separated from the RF equipment. To equalize differences of the electrical lengths of the two orthogonally polarized channels, a compensation cable preceding one demodulator must be provided. Because of the similar tasks, the concept of the XPIC itself is very similar to that of the ATDE. Thus the canceller transversal filter is also realized as a parallel-in serial-out structure and the same multiplication and delay elements could be used with few modifications [8]. A bipolar semi-custom monolithic integrated circuit is also used for controlling the tap weights and the integrators are designed as miniaturized modules with a novel auto-zero technique.

The "XPIC control" circuitry is of considerable complexity because many different situations in both transmission channels have to be taken into account. As a consequence, many different operating conditions have to be monitored continuously, and corresponding reactions have to be produced.

The supervision concept of the XPIC is in detecting circuit and equipment disturbances. This involves a complete disabling of the XPIC's function. A signal indicating "XPIC operation" is also provided. The supervision signals are available at the interface plug-in.

Experimental results

Fig. 9a–e shows original oscillograms illustrating the canceller's capability of operating with plesiochronous data signals. **Fig. 9f** shows the setup for this measurement. The traces of each oscillogram represent the signals, A (undisturbed transmitted signal with horizontal polarization), B (interfering signal from vertical transmitter to horizontal receiver), C (disturbed received signal with horizontal polarization) and D (reestablished horizontal signal after cancellation).

Plesiochronous clock frequencies result in a continuous change of the phase difference. Thus, the four oscillograms are taken at four phase differences (0°, 90°, 180°, 270°), demonstrating a constant good cancellation performance for each case and confirming the plesiochronous operation capability.

As mentioned before, the delay difference of the vertically and horizontally polarized channels must be equalized with an additional compensation cable. This compensation method is inherently afflicted with a residual error. In addition, this error is increased in a real cochannel system by aging and temperature-dependent effects.

As an additional advantage, a fractionally-spaced canceller filter automatically compensates these delay differences. In **Fig. 10** a comparison of baud-spaced and fractionally-spaced filters is given. The minimum required XPD is plotted against the delay difference and it is obvious that the fractionally-spaced solution offers superior results.

Conclusions

The inset of a cross-polarization interference canceller for the DRS 140/... radio family was presented. The XPICs are designed for non-synchronized data signals. They can be optionally incorporated into existing radio systems. The fractionally-spaced structure of the transversal canceller filters together with their insertion preceding the ATDE offers the best trade-off for a great variety of cross-polarization interferences and facilitates delay equalization of both orthogonal channels.

The XPIC is available for the 16- and 64-QAM modulation schemes. Owing to increased sensitivity of 64-QAM to cross-polarization interference, an XPIC will be a necessity for almost all hops. Such cancellers are paving the way to bandwidth efficiencies up to 10 bit/s/Hz without necessitating 4096 modulation levels. Cochannel operation is, therefore, a very attractive solution to the task of achieving utmost bandwidth efficiency in digital radio transmission.

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Family of Digital Radio Relay Systems with 16 QAM for 140-Mbit/s Transmission in Long- and Medium-Haul Links

A family of digital radio relay systems for the transmission of 140 Mbit/s signals over long-haul and medium-haul links is described. These systems employ 16-level quadrature amplitude modulation (16 QAM) and operate in the classic long-haul frequency bands of 3.9 GHz, 4.7 GHz, 6.7 GHz and 11.2 GHz, as well as in the 13-GHz and 15-GHz bands. These systems were designed to permit continued use of the available infrastructure on existing radio relay links and to employ the customary hop lengths, while conforming to CCIR recommendations on transmission quality and availability. Moreover, by making use of the two orthogonal polarizations of one radio frequency, the bandwidth efficiency in the classic long-haul frequency bands with their 40-MHz channel spacing can be increased by a factor of two from 3.5 bit/s/Hz up to 7 bit/s/Hz. Co-channel operation can be used to solve frequency coordination problems, e.g. in the higher RF bands (15 GHz) with their 28-MHz channel spacing, in this way maintaining the bandwidth efficiency of 5 bit/s/Hz.

After a brief discussion of the main constraints and principles, the authors present the concept adopted in this system family and describe the design of the various system units.

General Constraints

With telecommunication networks converting from analog to digital systems, transmission equipment is required to provide on an economical basis suitable and adequate transmission capacity for digital signals at all levels of the network including long-haul links. In the radio relay field, the capacity requirement per radio frequency (RF) channel is based on the capabilities of established analog radio relay systems, which in the classic long-haul bands employ frequency modulation (FM) to provide transmission capacities of 960, 1800 or 2700 voice channels per RF carrier. The most appropriate transmission capacity for long-haul links on digital radio relay systems is, therefore, the fourth-order level of the digital hierarchy at 139.264 Mbit/s (abbreviated to 140 Mbit/s).

Since for economic reasons conversion of the networks from analog to digital transmission can only be a gradual process, it will be necessary for analog and digital radio relay systems to coexist during the transition period. During this period, digital radio relay systems will generally be using the same frequency bands with the same channel arrangements and the same infrastructure as analog systems. They must, therefore, be as fully compatible with them as possible.

For analog radio relay systems operating in the 6.7- and 11.2-GHz bands, the CCIR has established frequency patterns with 40-MHz channel spacing (Recommendations 384-3 and 387-3) which are also adopted in the 4.7-GHz band. In the 3.9-GHz band a new homogeneous 10-MHz pattern (Recommendation AA/9) has been defined for use with digital systems. In these three long-haul bands it is thus possible to assume frequency patterns employing uniform 40-MHz channel spacing. In the 13-GHz and 15-GHz band the CCIR recommends a channel spacing of 28 MHz for transmitting 34 Mbit/s (Recommendation 497-2 and 636). There is, however, also a desire to provide a transmission facility for 140-Mbit/s signals in the 28-MHz arrangement for applications in the long-haul and medium-haul network, but this will entail restrictions on hop length.

Spectrum utilization with multilevel QAM

Multilevel quadrature amplitude modulation [1, 2] is nowadays the preferred modulation method for high-capacity

	Channel spacing		
Bandwidth efficiency in bit/s/Hz	40 MHz		28 MHz
	interleaved	cochannel	
3.5	$\varrho = 0.5$	–	–
5.0	–	–	$\varrho = 0.5$
7.0	–	$\varrho = 0.19$	–

Table 1 Required roll-off factor (ϱ) for 16 QAM systems

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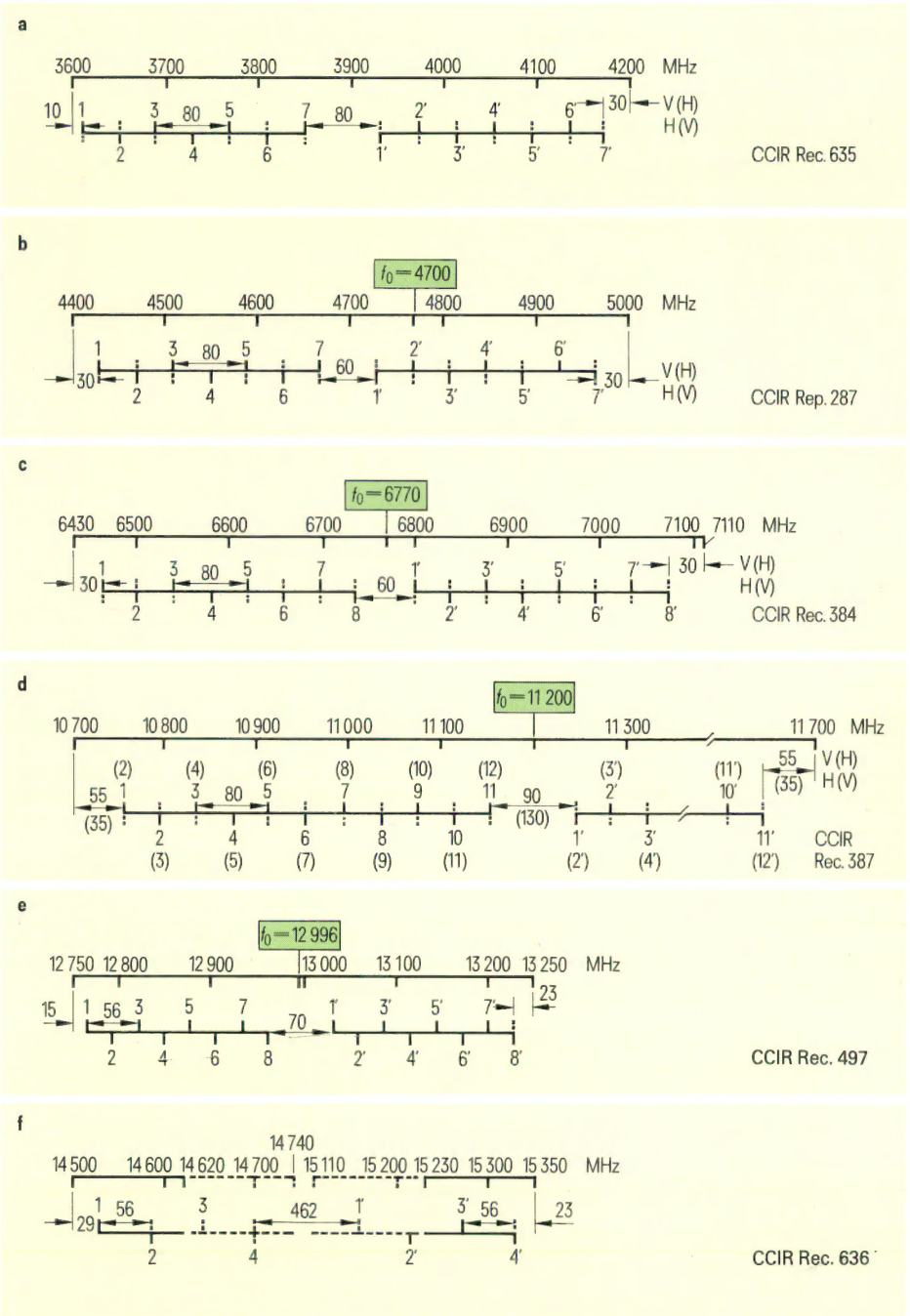
digital radio relay systems because, for a given spectrum utilization, it has a much lower signal-to-noise ratio requirement than phase-shift keying with the same number of states. As **Table 1** shows, the spectrum utilization of 3.5 bit/s/Hz required for the transmission of signals at 140 Mbit/s in 40-MHz wide channels can, in principle, be achieved with 16 QAM. Assuming that the Nyquist filtering is ideally partitioned in equal measure between transmitter and receiver (using square root Nyquist filters), the adjacent channel isolation with a channel spacing of 40 MHz and roll-off factors up to about 0.14 ($\varrho \leq 0.14$) is ideal (infinite). For common values of $\varrho \approx 0.5$, a channel spacing of 40 MHz produces slight overlap and 28 MHz severe overlap, which even with ideal spectra and filters provides an adjacent channel isolation of only about 17 dB and 6 dB, respectively.

Because a signal-to-noise ratio (S/N) of at least 28 dB must be maintained in order to keep the background error ratio below 10^{-10}, an additional isolation of at least 14 or 25 dB is thus required (for two interfering spectra and with $\varrho = 0.5$). This isolation must be provided by operating the adjacent RF channels on an orthogonal polarization. The cross-polarization discrimination (XPD) values required for 40-MHz spacing can be maintained with a large margin using ordinary antennas.

Even if the XPD values decrease due to anomalous propagation conditions on the radio hop, this rarely leads to problems. By contrast, the XPD values required for 28-MHz spacing are on average just obtained when the usual antennas are used. In practice, the effect of adjacent channels in this case, even without the propagation-related deterioration in XPD, produces a degradation of the system characteristic which, although slight, is not negligible (≤ 1 dB for a bit error ratio (BER) of 10^{-6}. If fading or precipitation attenuation occur in the hop, the resultant decrease in XPD values will affect the transmission quality and availability to an extent that can only be tolerated in the medium-haul network where the hop lengths are generally shorter.

From this, it can be concluded, that the roll-off factor must be drastically reduced to allow for cochannel operation on the two orthogonal polarizations with 40-MHz channel spacing. To end up with a negligible adjacent channel interference, a $\varrho = 0.19$ has to be implemented (**Table 1**) [3]. To keep cochannel interference down to the required level, high XPD antennas are advantageous; in most unfavorable conditions, a cross-polarization interference canceller (XPIC) must be utilized [4].

Cochannel operation in the 13-GHz and 15-GHz bands cannot double the bandwidth efficiency, because the adjacent copolarized channel cannot be operated with only 28-MHz channel spacing. In these bands cochannel operation can solve frequency coordination problems



f_0 Band center frequency f_r Reference frequency of the main pattern

Fig. 1 Radio frequency (RF) channel arrangement for the family of radio relay systems, DRS 140/3900, 6700, 11200, 13000 and 15000 (frequencies in MHz)

a DDR 140/3900
b DRS 140/4700
c DRS 140/6700
d DRS 140/11200
e DRS 140/13000
f DRS 140/15000

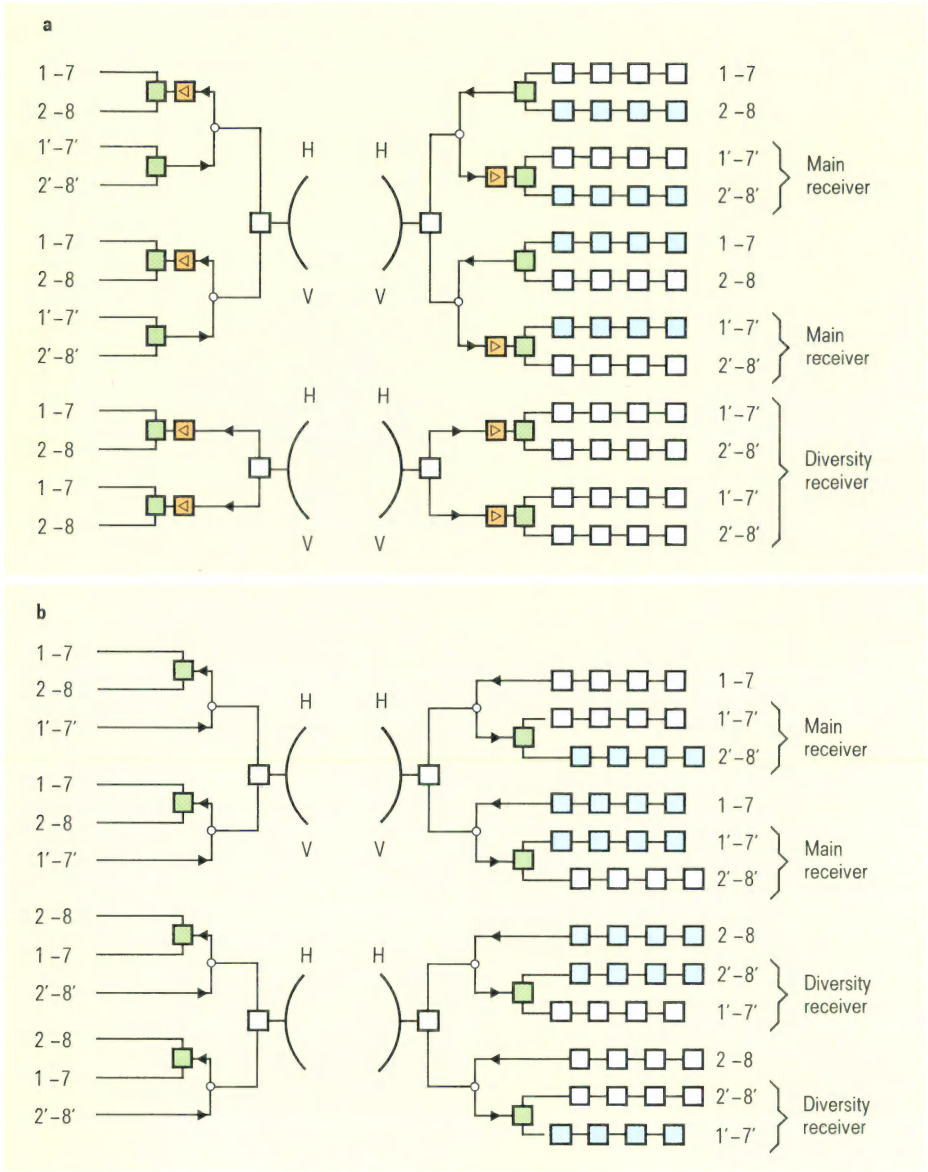


Fig. 2 RF channel/antenna arrangement

a Co- and adjacent channel transmitters on the same antenna
b Chochannel transmitters on the same antenna; adjacent channel transmitters on different antennas

by reducing undesired out-of-band emissions, while maintaining the same bandwidth efficiency of 5 bit/s/Hz (**Table 1**). Depending on the hop length, an XPIC may be necessary in many situations.

General system concept

The preceding considerations demonstrate that 16 QAM provides an optimum modulation method for transmitting signals at 140 Mbit/s with a channel spacing of 40 MHz and, subject to certain restrictions, for transmission with 28-MHz channel spacing. Accordingly, the method of modulation adopted on the family of digital radio relay systems for transmitting 140-Mbit/s signals, discussed in this article, was 16 QAM.

A raised cosine roll-off characteristic was specified for pulse and spectrum shaping. The roll-off factor is either $\varrho = 0.5$ or $\varrho = 0.19$ (**Table 1**).

With exacting demands on signal-shaping precision, on modulation and demodulation coupled with the need to employ an identical modulation method for six RF bands, the system concept adopted was based on indirect modulation at the intermediate frequency (IF).

The indirect IF modulation concept permits some additional system features:

- The systems are prepared for an economic IF through-connection mode of operation, without regeneration modems for up to four hops, depending on the specific climatic conditions and path characteristics.
- 2-Mbit/s wayside traffic signals can be dropped from and inserted into the IF at every repeater or terminal station. The method uses reduced power IF subcarriers which are added above or below the 140 Mbit/s signal spectrum. Such subcarrier signals fit well into the excessive bandwidth of the RF channel filters.

The family of systems thus comprises identical modulator and demodulator units but transmitters and receivers which are specific for the particular RF band. The interfaces between the modulation or demodulation units and the RF units are located at the intermediate frequency of 140 MHz. The design and characteristics of the modem are described in a separate article [5].

The three units designed for specific RF bands, comprising the transmitter, main receiver and diversity receiver, are based on largely identical electrical concepts. The essential differences lie in the transmitter. The transmit amplifiers for the three lower frequency bands employ exclusively GaAs field-effect transistors (FET), while power amplifiers with traveling-wave tubes are available for the higher frequencies if higher transmit powers are required.

RF channel arrangements

Fig. 2 shows the channel arrangements specified in the relevant CCIR recommendations for the various frequency bands. In the four lower bands at 3.9, 4.7, 6.7 and 11.2 GHz, adjacent channels all have 40-MHz spacing. In addition, they are generally operated on orthogonal polarizations. The minimum frequency spacing on a channel branching filter chain is 80 MHz.

The DRS 140/3900 digital radio relay system is designed for the frequency band, 3400 (or 3600) to 4200 MHz. Since the center gap is 80 MHz, the required center gap isolation is obtained without

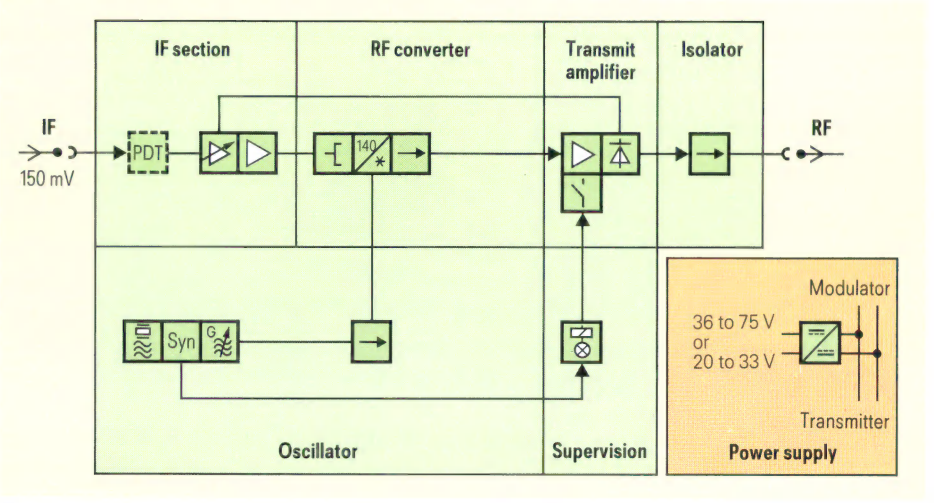
further measures. Altogether it is possible to transmit nine or seven channel pairs in parallel in both directions.

The DRS 140/4700 radio relay system can be utilized in the frequency band, 4400 to 5000 MHz. Because of the 60-MHz center gap, the same precautions apply as described below for the DRS 140/6700. Altogether in the interleaved pattern configuration a total of seven channel pairs can be transmitted.

The DRS 140/6700 radio relay system can be employed in the frequency band, 6425 to 7125 MHz. With the center gap specified for this band being merely 60 MHz, the two center gap channels, 8 and 1′ can only be used without significant restrictions if there is excellent spectrum limiting in the modulator and transmitter and greater RF selectivity provided by special reduced-bandwidth channel branching filters. This produces a slight degradation of the system characteristic and a slightly reduced system gain in the center gap channels. The usability of these two channels is impaired only to an insignificant extent and allows all eight RF channel pairs to be used in both directions using only one antenna.

The DRS 140/11200 radio relay system covers the frequency band from 10,700 to 11,700 MHz. For this band, CCIR Recommendation 387 provides up to 12 RF channels with 40-MHz spacing. Owing to the low spacings at the edges, however, the outermost corner frequencies are not suitable for digital transmission at 140 Mbit/s. Using the main and interleaved patterns, it is possible to implement various channel arrangements each with 11 RF channel pairs. The RF channels at the 90-MHz wide center gap are either co- or cross-polarized. A channel arrangement with a 130-MHz wide center gap is also possible.

Doubling the bandwidth efficiency is feasible for all four frequency bands by converting the system from $\varrho = 0.5$ to $\varrho = 0.19$ [3]. This conversion can easily be carried out mainly by using special SAW filters in the IF sections of the transmit and receive units of the radio system and by inserting linearization means in the transmitter. This is a very attractive approach to increasing the capacity of existing routes while reusing the existing antennas and radio equipment with only minor modifications. Moreover, the substantially decreased spectrum bandwidth with $\varrho = 0.19$ can be used as an effective means of reducing frequency coordination problems arising when different operating companies have to share the same band.



G Generator
IF Intermediate frequency
RF Radio frequency
PDT Predistorter, used only with traveling-wave tube transmit amplifier
SYN Synchronization

Fig. 3 Functional diagram of the transmitter for the radio relay system family, DRS 140/3900, 4700, 6700, 11200, 13000 and 15000.

RF channel/antenna arrangements have been developed for the transmission of all RF channels in both directions, including space diversity, using only two antenna. **Fig. 3** shows two solutions, the relative advantages of which are discussed in detail in [3]. Furthermore, it is advisable that FM and digital radio systems, which must coexist on the same hop using the same frequency band and channel allocation plan, should transmit from the same antenna.

The DRS 140/13000 radio relay system operates in the frequency band, 12,750 to 13,250 MHz, for which the CCIR in Recommendation 497 specified a channel spacing of 28 MHz with a total of eight RF channel pairs which was originally intended for medium-capacity analog and digital systems. With the restrictions previously stated and with special measures to ensure adequate cross-polarization discrimination (antennas with high XPD, space diversity), it is possible to use 16 QAM to transmit 140-Mbit/s signals in this channel arrangement. Moreover, it is possible to operate this system on a link in combination with the DRS 34/13000 system [6], e.g. by duplexing the two systems on separate orthogonal polarization planes.

The DRS 140/15000 radio relay system is designed for operation in the frequency band, 14,500 to 15,350 MHz. Four RF channel pairs in this band can be established with cochannel operation without undesired out-of-band emissions, in this way avoiding frequency coordination problems.

Facilities for assuring transmission quality

Digital radio relay systems employed in the long-haul network are covered by the quality and availability recommendations for high-grade circuits in accordance with the relevant CCITT and CCIR guidelines [7]. If the permissible percentages for degraded minutes ($BER \geq 10^{-6}$) and severely errored seconds ($BER \geq 10^{-3}$, or signal loss for less than ten consecutive seconds) are not to be exceeded, it is not enough in the case of digital radio relay systems employing multilevel modulation merely to design the system or link to provide an adequate system margin against flat fading. It is much rather the linear distortion in the transmission channel due to multipath propagation in the radio hop (multipath fading or dispersive fading) that has proved to be the main cause of impaired transmission quality (with increased bit error ratios and even signal loss). To match the incidence and intensity of such propagation anomalies, both aspects of which depend on the conditions in the radio hop of interest, the family of systems described in this article

provides a series of effective, graded multipath countermeasures to assure the required transmission quality.

The regeneration of the digital signal always provided on the receive side in the demodulator substantially suppresses additive interference (noise) and provides a certain, although not usually adequate, immunity to distortion.

An effective but relatively simple means of compensating moderate distortion is available in the form of adaptively operating amplitude equalizers in the intermediate frequency band. With its favorable performance to cost ratio, particularly for minimum-phase distortion, an IF amplitude equalizer of this type is provided in every radio relay receiver. A more effective, but also more involved countermeasure against more severe, both minimun and nonminimum, phase distortion is available in the form of space diversity receive systems and, more particularly, adaptive time-domain equalizers (ATDE).

In a diversity receive system, two or more signals received from antennas at different heights (typical diversity spacing 5 to 15 m) are detected and combined to form an optimized sum signal (e.g. at IF). With suitable design, the effects of very deep selective fading with the resultant amplitude and delay distortions can be largely eliminated.

Frequency diversity receiving systems operate on a similar principle to space diversity systems. However, they require hitless $(N+1)$ switching [8] and an additional RF channel.

The most effective means of countering the effects of fade-related signal distortion is the adaptive baseband equalizer operating in the time domain and available either in addition to or sometimes in place of diversity receive systems [5]. Used in conjunction with a space diversity receive system, this device enables the relevant CCIR quality recommendations to be maintained even on hops with difficult propagation conditions.

For systems employing cochannel operation with 40-MHz channel spacing, the demodulator with ATDE is recommended on every hop. This demodulator inset is the one that provides the necessary interfaces allowing for cooperation with an XPIC. Such an XPIC might be necessary to counteract severe multipath induced depolarization effects encountered on very unfavorable hops.

In the frequency bands above 10 GHz, depolarization due to rain is the main reason for cochannel interference and, depending on the hop length, necessitates the use of the XPIC [1].

Compatibility with analog radio relay systems

In the RF bands, 6.7 and 11.2 GHz, analog radio relay systems are in operation with transmission capacities of 1800 and 2700 voice channels. In principle, it is possible to operate a mixture of analog and digital radio relay systems on one route, i.e. on a compatible basis, if an adjacent channel separation of 40 MHz is provided for cross-polarized or 80 MHz for copolarized operation. It is usually even possible to make use of the spare capacity on existing antenna systems and channel branching filter chains. The most noticeable interference resulting from this is produced in an analog radio relay system with 2700 voice channels by a 140-Mbit/s radio relay system with 40-MHz channel spacing. The actual value of the noise depends on the current value of cross-polarization discrimination (XPD). In the series of digital radio relay systems presented here, however, the spectrum limiting is such that it does not exceed 10 pW in the worst channel. As a result of the compact FM spectrum, the noise in the digital system is negligible despite the considerably higher transmit power of the analog system.

In radio relay networks with mixed traffic it is advisable to investigate the possible noise sources separately. It may be necessary to modify branching filters or provide additional or special filters in the adjacent analog and digital radio relay systems, depending on the manufacturer systems combined at the node.

Equipment units employed in the family of systems

As previously stated, the modulation and radio sections in the family of systems presented here were realized as separate units. The DRM 140/140-16 modem insets described in [5] are interchangeable units common to all systems in this family.

All the measures required for pulse and spectrum shaping (square root of Nyquist filtering) are provided in the modulator and demodulator insets. This is true with one exception: cochannel operation in 40-MHz channel spacing. In this case the receiving SAW filter with a $\varrho = 0.19$ is inserted in the main receiver inset in front of the main IF amplifier and adaptive frequency domain equalizer to protect these modules from adjacent channel interference.

In the radio sections the modulated signal is translated from the IF to the RF band and amplified. When multilevel modulation methods (e.g. 16 QAM) are employed, the signal processing must introduce as little distortion as possible. Nonlinear distortion due to the modules in the signal path would otherwise produce considerable degradation of the system characteristics. The transmitter and receiver including the channel branching filters are basically transparent units in which only the signal level and signal center frequency are different.

The interfaces between the modem units and the radio sections are located at the intermediate frequency of 140 MHz. This separation between radio sections and modems also confers advantages regarding the stocking of spares and facilitates the testing and maintenance of equipment. The design and operation of the radio sections are described in the following paragraphs with reference to their functional diagrams.

Transmitter

As can be seen in **Fig. 3**, the transmitter inset incorporates the individual functions for the *IF amplifier, up-converter, carrier supply, transmit amplifier* and *transmitter supervision*. In order to meet the requirements for minimum nonlinear distortion with maximum efficiency, the signal power at the output of the RF power amplifier is stabilized by a control circuit. The gain control to compensate input level variations and temperature-dependent gain effects is provided in the IF input amplifier.

The 140-MHz intermediate frequency signal from the modulator is fed via the gain-controlled input amplifier and a special low-distortion driver amplifier to the single-sideband converter, which translates the IF signal to the RF band. The carrier and the unused sideband are sufficiently suppressed to eliminate the

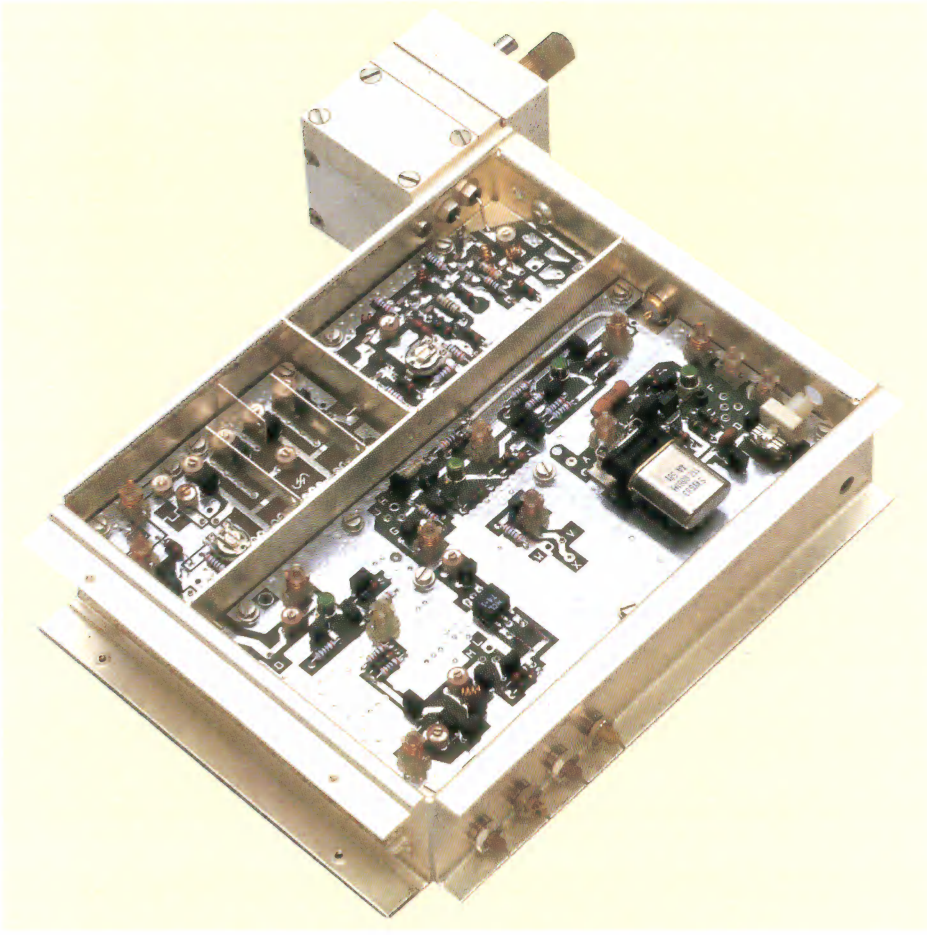
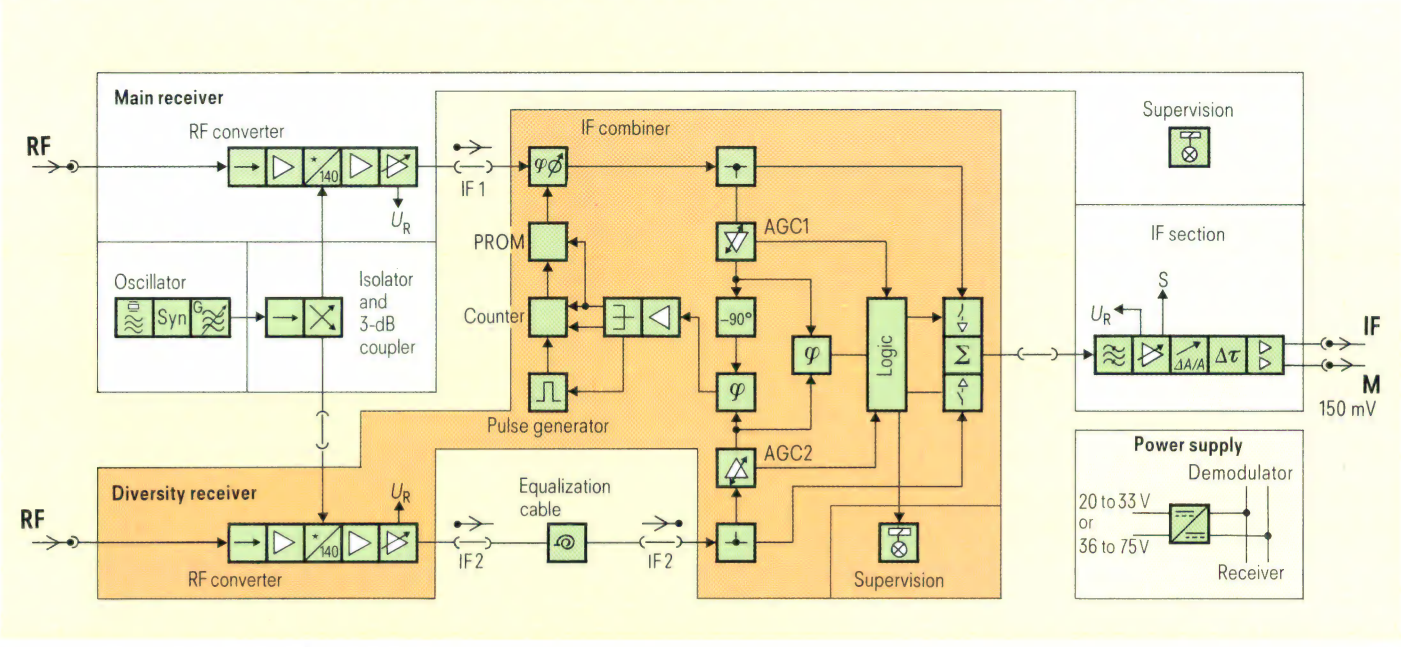


Fig. 4 Radio frequency (RF) carrier supply of the DRS 140/6700 digital radio relay system

need for a channel-specific sideband filter in the transmitter [9].

Frequency-stabilized and mechanically tunable microwave oscillators produce the local oscillator signal required for the conversion. The active devices employed are silicon bipolar transistors (for 3.9 GHz , 4.7 GHz and 6.7 GHz) and Gunn devices (11.2 GHz, 13 GHz and 15 GHz). A change of transmit frequency can be readily performed on site with the central meter provided.

The RF signal at the converter output is raised to the final transmit level by a transmit power amplifier which has to meet high linearity requirements. The frequency bands, 3.9 GHz, 4.7 GHz, 6.7 GHz and 11.2 GHz, employ solid state power amplifiers with a nominal transmit power of 1 W and an output power of about 5 W at the 1-dB compression point. Transmit amplifiers with a nominal output power of 5 W are optionally available for the 11.2-GHz band and are always provided in the form of highly linear traveling-wave tube amplifiers for the 13-GHz band. These high transmit powers cannot yet be produced economically for this frequency by semiconductor amplifiers. The traveling-wave tubes employed have a (theoretical) saturation



* 3900, 4700, 6700, 11200, 13000 or 15000 MHz

$\Delta A/A$	Adaptive IF amplitude equalizer	IF	Intermediate frequency	S	Supervision
AGC	Automatic gain control	M	IF test output	SYN	Synchronization
φ	Phase comparator	PROM	Programmable read only memory	Δe	Delay Equalizer
$\varphi\varnothing$	Endless phase shifter	RF	Radio frequency	U_R	Control Voltage
G	RF generator				

Fig. 5 Functional diagram of the modular receive system of the family of radio relay systems DRS 140/3900, 4700, 6700, 11200, 13000 and 15000 with space diversity as an option

power of about 35 W and are fed directly from the station battery via a separate high-voltage converter independent of the transmitter power supply.

The dynamic range of the traveling-wave tube amplifier and hence the available linear output power is significantly improved by compensating the slight tolerance-related and frequency-dependent tube distortion. This linearization by a drive-dependent predistorter is provided in the IF band.

This predistorter may also be employed in conjunction with the solid-state power amplifiers (SSPA) in the 3.9-GHz, 4.7-GHz and 6.7-GHz system in the case of cochannel operation. This together with a slight reduction of the average transmit power by 1 dB meets the increased linearity requirements caused by the enhanced signal peak values due to the reduced $\varrho = 0.19$ [3].

A level probe monitors the power at the amplifier output. It also produces the actual signal for automatic control of the transmit power. If the carrier supply malfunctions (loss of synchronization), the transmit amplifier is disabled by an electronic switch to prevent the radiation of interfering signals.

The transmit carrier supply of the DRS 140/6700 digital radio relay system shown in **Fig. 4** is a typical example of the RF modules.

Receiver

The receive side shown in **Fig. 5** comprises the two equipment insets for the *main receiver* and *diversity receiver*. The latter is required for space diversity reception and enables the effects of selective fading to be largely eliminated by permitting two receive signals to be combined.

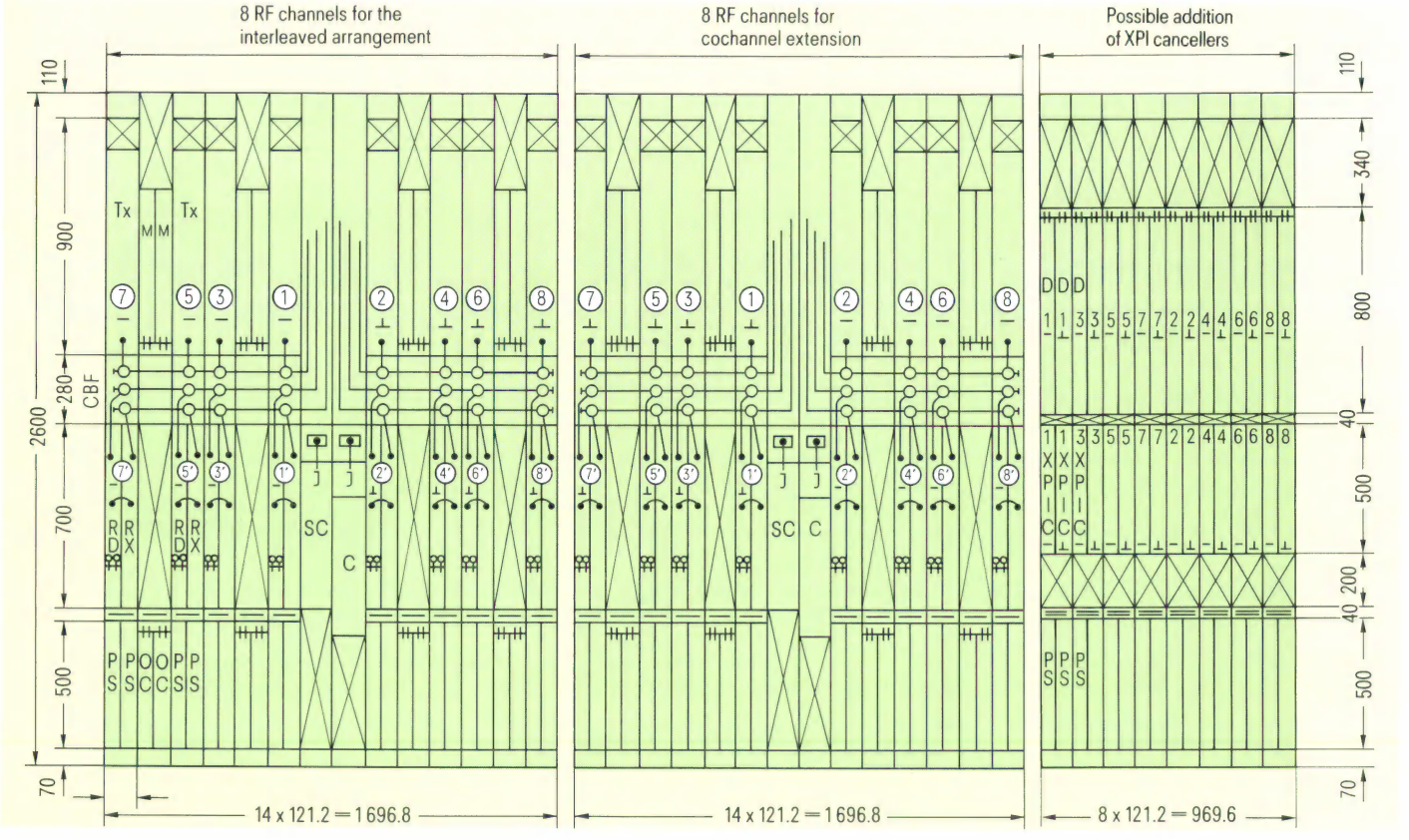
Main receiver

The main receiver inset incorporates the functions required for single-signal reception, i.e. the *RF converter, carrier supply, IF preamplifier, IF section with IF filter, main IF amplifier, delay equalizer* and *adaptive IF equalizer* as well as the *receiver supersivion circuit.*

The *RF converter* always contains a low-noise RF preamplifier which by virtue of its low noise figure produces an improved system gain. Translation to the IF at 140 MHz is effected with a single-sideband converter [9]. The *carrier supply* is similar to that in the transmitter.

The local oscillator signals are available at two identical outputs for driving the down-converters of the main and diversity receivers. A low-noise, gain-controlled and overload-proof *IF preamplifer* raises the signal level. During single-signal reception, the output signal from this preamplifier is through-connected directly to the main IF amplifier in the main receiver. During diversity reception, it is fed to the IF combiner in the diversity receiver. The dual requirement for low system noise figure and high linearity is optimally met by the gain control in the IF preamplifier.

The *IF section* module is provided with the *IF filter* to suppress adjacent channel



⊥	Vertical } polarization	J	Meter	SC	Service channel inset
—	Horizontal }	M	Modulator	SW	Switching inset
	(dimensions in mm)	OC	Operating channel	TX	Transmitter
C	(1+1) control inset	PS	Power supply	XPIC	Cross-polarization interference canceler
CBF	Channel branching filter arrangement	RX	Receiver		
D	Demodulator	RD	Diversity receiver		

Fig. 6 Rack configuration for the family of radio relay systems DRS 140/3900, 4700, 6700, 11200, 13000 and 15000.

Fig. 7 Rack insets of the DRS 140/6700 radio relay systems: transmitter, main receiver, diversity receiver, demodulator, modulator, two power supplies, switching inset and (1+1) control inset of the DESG 140 protection switching equipment (from left to right)

signals. The gain-controlled *main IF amplifier* operates in conjunction with the IF preamplifier to raise the level to a constant value at the output, provided that the receive level lies within the control range. Since the control signal at the output of the IF section is derived via band-pass filters, any interference with the output level due to adjacent channel signals is eliminated and the remaining level errors due to the equalizers are removed.

An adaptive *IF amplitude equalizer* is used to equalize the amplitude distortion due to multipath propagation (selective fading) on the hop. Control signals derived by weighting the receive spectrum in three spectrum windows are applied via control elements to equalize the signal spectrum.

The group delay distortion introduced by the filters in the signal path is equalized via three equalizer stages. The delay slopes introduced by the branching filters of the adjacent channels can be equalized by adjustment in fixed increments to suit the channel branching filter loading. The IF transfer level to the following demodulator is produced with low distortion by highly linear IF output stages.

Diversity receiver

The diversity receiver contains an *RF converter module,* which is similar to that of the main receiver, and the *diversity combiner* which operates in the IF band.

The receive signal from the diversity antenna is down-converted, with the same local oscillator signal to ensure that the resultant IF signal has no frequency offset with respect to the IF signal obtained from the main receiver. The two signals are then added in phase with equal weighting in the IF combiner to produce the maximum sum power (maximum power combiner). The IF signal from the receiver with the shorter waveguide feeder length to the antenna is passed through a delay line to compensate the delay differences due to the

differing lengths of the antenna feeders. This line is accommodated in its own small inset assigned to the receiver rack.

The second IF branch of the combiner (**Fig. 5**) incorporates an endless phase shifter which is adjusted digitally via a control loop to ensure that in the summing network the signals from the main and diversity antennas are added in phase. In order to compare the phases of the two channels in an analog phase detector, signal samples are extracted and each of them is raised to a constant level in a gain-controlled amplifier.

The two branches are monitored for level differences via the AGC (automatic gain control) voltages of the two gain-controlled amplifiers. If the difference exceeds 10 dB the branch with the lower (less favorable) level is electronically disconnected.

It is not neccessary to assign the two receive branches to the antennas according to the differing feeder lengths since the delay equalizing line can be assigned within the unit. Level differences between the two branches due, for instance, to differing antenna sizes can also be equalized.

In the case of cochannel operation with XPIC, the carrier supplies of the vertical and horizontal receiver of the same radio frequency are synchronized in order to avoid a frequency offset between the place where the crosstalk between polarization occurs and the place where it is cancelled with the aid of the XPIC. The canceller insets themselves are – like the modem – identical for the whole family of systems [4].

Equipment power supply

The transmit and receive sides are each assigned separate but identical power supply insets designed for operation from battery supplies ranging from 36 to 75 V (floating). The operating voltage which they provide for the equipment insets are short-circuit proof and isolated from the primary side. The modem insets are also operated from these power supplies.

In the case of cochannel operation with XPIC, either one demodulator and one canceller inset or two canceller insets can be operated from one of the supply units mentioned above.

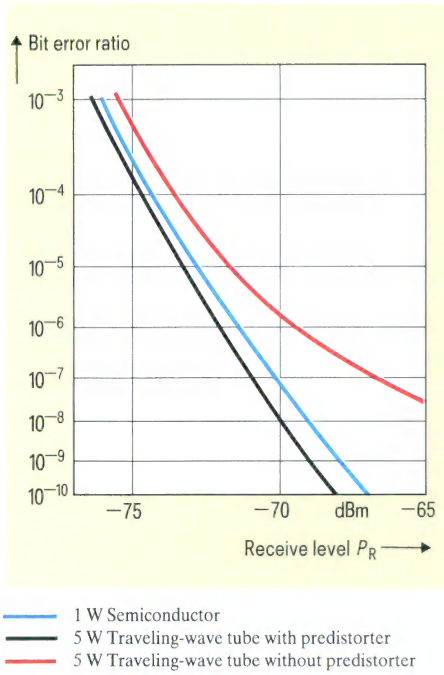


Fig. 8 Typical system characteristics (bit error ratio as a function of receive level) for the DRS 140/11200 radio relay system

System supervision

The supervision modules are accommodated in the equipment insets on the transmit and receive sides. Any faults are generally indicated by light-emitting diodes in the defective inset and by passing on an alarm signal. The alarm signals on the *transmit side* are:

- loss of baseband signal at the modulator input (MS1),
- loss of frame clock and data in the modulator (MS2),
- loss of IF signal at the modulator output (MS2),
- loss of synchronization in the carrier supply (MS2),
- loss of transmit output power (MS2),
- equipment fault, e. g. voltage failure (MS2).

The alarm signals on the *receive side* are:

- loss of channel identification or inadequate transmission quality (ML),

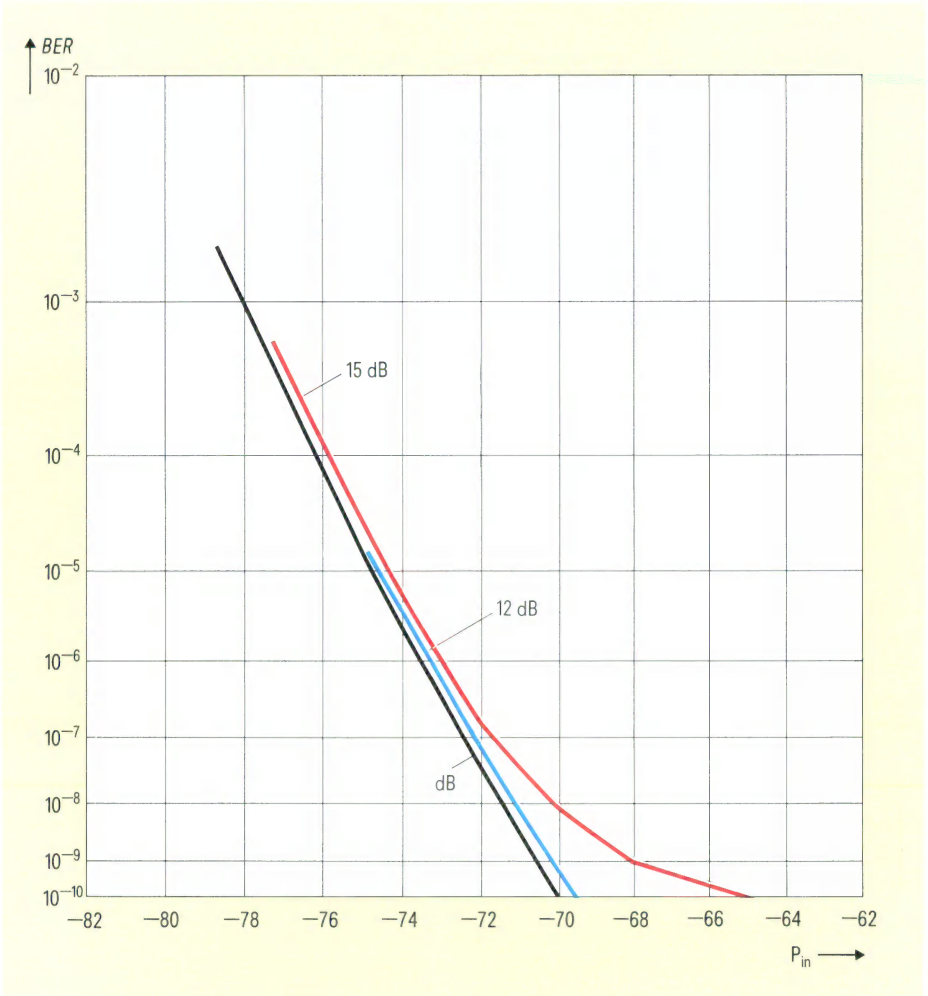


Fig. 9 Adjacent channel interference ($\varrho = 0.19$; 6.7 GHz); parameter: level difference between wanted and adjacent signal (40 MHz apart)

- loss of synchronization in the carrier supply (ME),
- loss of IF input level at the demodulator, loss of frame clock (ME).
- equipment fault (ME), e.g. voltage failure,
- IF combiner failure (ME).

The fault signals, MS1 and MS2 as well as ML and ME, are passed to a remote supervision unit via isolating contacts; they are also used as switching criteria for a protection switching equipment. Faults which result in the interruption of the wanted signal initiate an alarm signal and are indicated visibly and audibly in the rack frame.

For fault location purposes, a centrally located meter is provided in the rack configuration and can be connected via a multicontact jack to the system insets. Using this central meter it is a simple matter to effect an RF channel change since the transmitter and receiver are of wideband design. Both the main and the diversity receiver have a recording output for the sum receive level or for the difference in receive level between the two branches.

Channel branching filters and connection to antenna

The channel branching filters on both the transmit and receive side consist of six-section filters with attenuation poles. They are designed with coaxial resonators for the 3.9-GHz band but with cavity resonators for 4.7 GHz, 6.7 GHz, 11.2 GHz and 13 GHz. Transmit and receive channel branching filters chains (formed by circulators and channel branching filters [10]) are coupled via a transmit/receive circulator and are connected via a common antenna feeder to a polarization plane of the antenna. For the diversity receive branch, all four systems require a separate channel branching filter chain similar to that in the main receive branch.

While up to five transmitters or receivers can be connected to a channel branching filter arrangement on the DRS 140/3900 radio relay system, this is possible for four transmitters or receivers on the DRS 140/4700, DRS 140/6700 and RS 140/13000 systems. On the DRS 140/11200 system it is possible to connect up to six transmitters or receivers. The antennas used can be existing

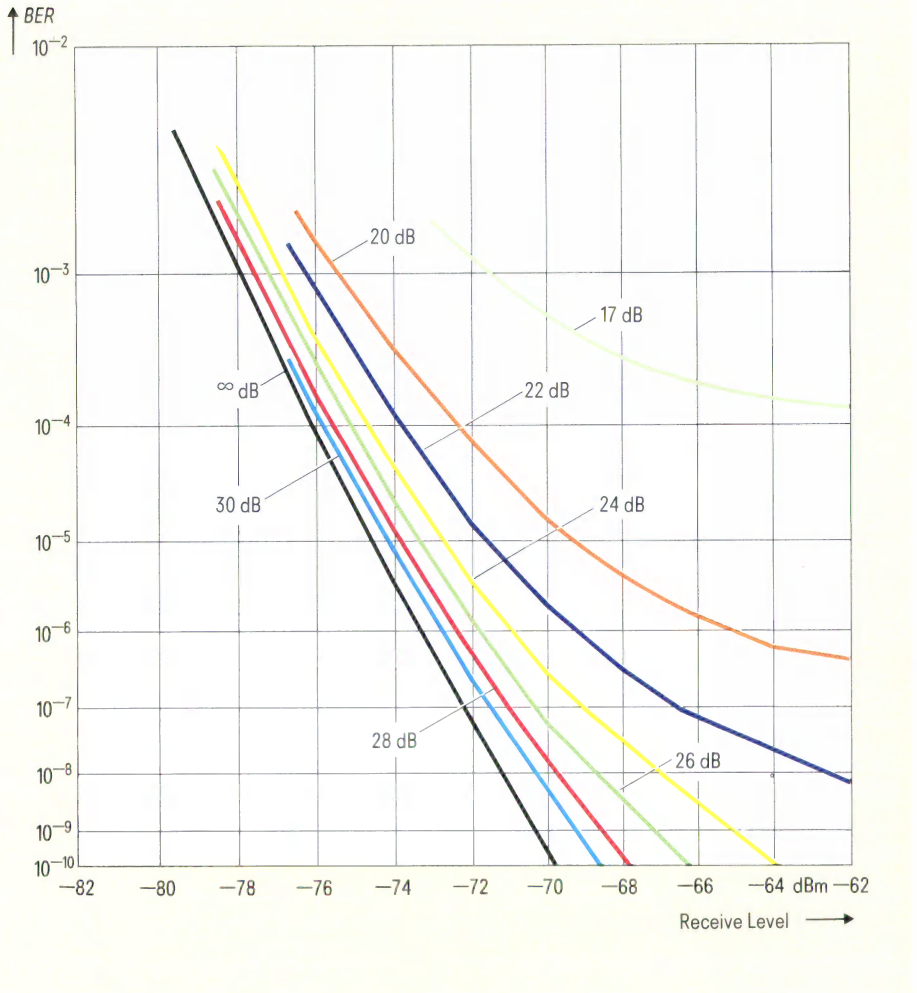


Fig. 10 Cochannel interference ($\varrho = 0.19$; 6.7 GHz); parameter: *S/N* level (e.g. XPD)

shell or parabolic types, depending on the network requirements. Greater planning and operating freedom is obtained, however, by using more modern antenna developments featuring improved cross-polarization discrimination and higher sidelobe attenuation [11].

Mechanical design and system characteristics

Three style 7R racks located side by side can accommodate – in the same configuration for all five radio frequency bands – two transmitters and two receivers (including diversity) with the associated modem and power supply insets and the insets of the (1+1) protection switching unit. The full extension to 16 RF channels in the 6.7-GHz band with the possible addition of the XPICs is shown in **Fig. 6**. A somewhat modified layout for making use of racks with reduced height (DRS 140/15000) is also available.

The transmitters and receivers are each assigned separate power supplies which are located side by side in the lower section of the rack. These supplies also serve the system modulator and demodulator units, which are mounted in an unwired empty rack between the two radio racks. On radio relay links with protection switching, the insets providing the (1+1) switching facility are mounted in the same rack as the modulators and demodulators. The switching and control insets of a (N+1) protection switching equipment can either be integrated in the system configuration or grouped in separate switching racks [8]. The terminal panel of the radio rack is the point of concentration for all the connections leading from the radio relay units to the outside.

Digital radio relay systems	DRS 140/3900	DRS 140/4700	DRS 140/6700	DRS 140/11200	DRS 140/13000	DRS 140/15000
General data						
Frequency range	3400 to 4200 MHz	4400 to 5000 MHz	6425 to 7125 MHz	10700 to 11700 MHz	12750 to 13650 MHz	14500 to 15350 MHz
Modulation	16 QAM	16 QAM	16 QAM	16 QAM	16 QAM	16 QAM
Number of possible RF channel pairs						
interleaved pattern	9	7	8	11 (12)	8	3**
cochannel operation	18	14	16	22	8 (10)*	4**
Minimum channel spacing on a channel branching filter	80 MHz	80 MHz	80 MHz	80 MHz	56 MHz	56 MHz
Transmission capacity	139.264 Mbit/s (1920 voice channels)	139.264 Mbit/s (1920 voice channels)	139.264 Mbit/s (1920 voice channels)	139.264 Mbit/s (1920 voice channels)	139.264 Mbit/s (1920 voice channels)	139.264 Mbit/s (1920 voice channels)
Center gap spacing	80 MHz***	60 MHz	60 MHz***	90 MHz or 130 MHz (50 MHz)	70 MHz	432 MHz
Transmitter						
Transmit power (mean; interleaved pattern)	30 dBm	30 dBm	30 dBm	30/37 dBm	35/37 dBm	35/37 dBm
Intermediate frequency	140 MHz	140 MHz	140 MHz	140 MHz	140 MHz	140 MHz
Transmit frequency drift	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$
Receiver						
RF input power	−34 dBm	−33 dBm	−32 dBm	−31 dBm	−30 dBm	−28 dBm
Permissible control range of receive power	−17 to −80 dBm	−17 to −80 dBm	−17 to −80 dBm	−17 to −80 dBm	−17 to −80 dBm	−17 to −80 dBm
Noise figure (typical)	3.8 dB	3.8 dB	3.8 dB	4.3 dB	4.5 dB	5 dB
Minimum receive power for 10^{-3} BER (typical)	−77 dBm	−77 dBm	−77 dBm	−76 dBm	−76 dBm	−76 dBm
Oscillator frequency drift	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$
System gain (minimum) (10^{-3} BER)	104 dB	104 dB	103 dB	103/110 dB	108/110 dB	107/109 dB
Power supply						
Battery voltage	20 to 33 V or 36 to 75 V	20 to 33 V or 36 to 75 V	20 to 33 V or 36 to 75 V	20 to 33 V or 36 to 75 V	20 to 33 V or 36 to 75 V	20 to 33 V or 36 to 75 V
Digital service channels	Omnibus channel (1 × 138 kbit/s) Express channels (2 × 138 kbit/s and 3 × 34.5 kbit/s)					

Antennas	3 m Shell-type	3 m Parabolic	3 m Shell-type	3 m Parabolic	3 m Shell-type	3 m Parabolic	3 m Shell-type	3 m Parabolic	3 m Parabolic	3 m Para-bolic****	2 m Parabolic
Frequency (GHz)	3.9		4.7		6.7		11.2		13.0		15.0
Gain (bandwidth)	38.5 dB	38.5 dB	41 dB	41 dB	43.5 dB	43.6 dB	47.3 dB	47.8 dB	48.2 dB	45.9 dB	46.5 dB
Front-to-back ratio	65 dB	60 dB	65 dB	60 dB	65 dB	60 dB	65 dB	65 dB	58 dB	65 dB	65 dB
Sidelobe attenuation											
50 dB	22°	50°	21°	50°	20°	50°	15°	13°	30°	63°	21°
60 dB	39°	95°	35°	87°	30°	80°	30°	85°	95°	77°	78°
65 dB	46°		40°		35°		35°	95°	98°	83°	84°

* In conjunction with $\varrho = 0.19$ and 42-MHz channel spacing
** Valid if only frequency bands, 14500 to 14620 MHz and 15230 to 15350 MHz, are available. An extension of these bands yields a corresponding increase in channel pairs
*** Cross-polarization
**** With radome

Table 2 Technical specifications for the DRS 140/3900, 4700, 6700, 11200, 13000 and 15000 family of radio relay systems

Fig. 7 shows the modulation and radio units of the DRS 140/6700 radio relay system, in the form of style 7R insets, as well as the associated power supply and protection switching units. While the transmitter occupies the full width of a rack (inset type I), the main and diversity receivers, as also the modulator and demodulator, are half a rack wide (inset type III) [12]. The digital and RF modules of the insets are designed largely with integrated circuits which produces a very compact design and high reliability. **Table 2** summarizes the principal data of all four members of the system family. **Fig. 8** shows the bit error ratio as a function of the receive level P_R for the DRS 140/11200 system.

One noteworthy feature in **Fig. 8** is the very narrow separation between the theoretical and experimental characteristics, indicating that degradation on this system implementation is very low. **Fig. 8** also shows that the degradation due to a traveling-wave tube operating at a transmit power of 5 W can be as low as that obtained with a 1-W semiconductor amplifier when the nonlinearity of the tube is compensated by a predistorter in the IF band.

The effect of adjacent channel interference (**Fig. 9**) and cochannel interference (**Fig. 10**) is shown for cochannel operation with 40-MHz channel spacing and $\varrho = 0.19$. Both figures prove that with the advanced SAW filters used, the interference from copolarized adjacent channels is negligible and the interference from the cross-polarized cochannel can be reduced by a high-XPD antenna sufficiently to make XPICs superfluous in many cases. A field experiment carried out with Telecom Australia demonstrated that this approach of increasing bandwidth efficiency while reusing existing equipment is an attractive, economic way of providing increased transmission capacity [13].

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Family of Digital Radio Relay Systems with 64 QAM for 140-Mbit/s Transmission in Long-Haul Links

The system family presented in this article is designed for high-grade transmission of 140-Mbit/s signals on long-haul links. In compliance with CCIR and CEPT recommendations, these systems operate in the frequency ranges, 2.1 GHz, 3.9 GHz and 6.2 GHz, with channel spacings of 29 MHz, 30 MHz and 29.65 MHz. They employ 64-level quadrature amplitude modulation (64 QAM) since it is a standard and suitable modulation scheme for channel spacings down to 28 MHz. The advanced features of the systems introduced here enable the more effective use of the frequency bandwidth and network resources.

Concept and system features

By combining 64-QAM modulation with the progressive surface acoustic wave IF roll-off filter technology [1], it was possible to implement the system family for cochannel operation. The two orthogonal polarizations can be utilized in this case independently for each radio frequency, thereby doubling the number of available RF channels in comparison to conventional interleaved pattern (IP) systems and raising the spectrum efficiency to 9.6 bit/s/Hz. This important feature improves the utilization of existing infrastructures (roads, buildings, towers, antennas etc.) effectively. Additionally, the particularly high adjacent channel isolation of the cochannel systems can be used to solve frequency coordination problems in dense networks, thereby preserving the maximum capacity of the radio networks for future capacity extensions. Beyond that feature, the reduced transmit spectrum bandwidth in many cases may present a solution for coexistence problems between networks of different operating companies as well as between different types of systems.

Considering these requirements, the system cochannel feature was conceived to be a safeguarding option, needing no preinvestment or preinstallation if introduced afterwards into interleaved pattern (IP) radio routes as capacity extensions become necessary. A basic aspect of the cochannel system design was to make adjacent channel spectrum interference negligible, so as to preserve the system interference margin exclusively for cochannel interference. Using a roll-off factor of $\varrho = 0.25$ (raised cosine roll-off) for the cochannel system version equally partitioned between transmitter and receiver (square-root Nyquist filters), an adequate interference reduction factor (*IRF*) larger than 44 dB was realizable. For the IP system version, where adjacent channels are isolated by the cross-polarization discrimination (XPD) of the antennas, a roll-off factor of $\varrho = 0.45$ with an *IRF* larger than 25 dB is sufficient. The reduced RF peak amplitude due to the larger roll-off factor of the IP version permits a 1.5 dB larger transmit power. Both system versions, however, differ only in the IF roll-off filter modules (**Fig. 1**) and are easily inter-convertible, mainly by exchanging these modules. Based on the above aspects, the three systems, DRS 140/2100-64, DRS 140/3900-64 and DRS 140/6200-64, were developed as a system family. Because these systems feature identical equipment insets, racks and IF and supervisory subunits, they combine

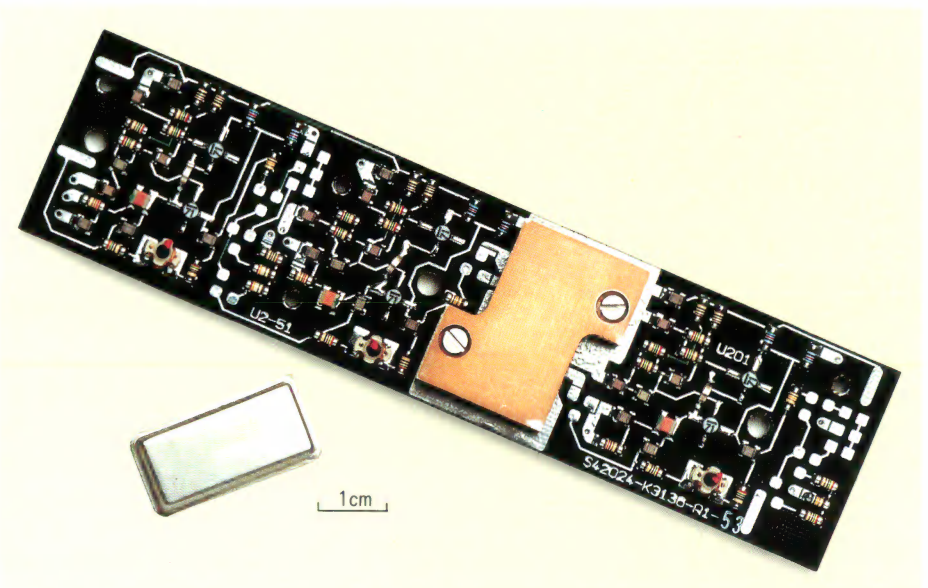

Fig. 1 SAW filter module employed in digital radio relay systems

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the advantages of largely identical electrical concepts and mechanical design, uniform operation and maintenance procedures, as well as simplified spare-parts stocking.

Indirect IF modulation is used with 70-MHz IF interfaces between the modem insets (modulator, adaptive time-domain equalizing demodulator and the cross-polarization interference canceller (XPIC) are presented in [2] and [3]) and the radio insets (transmitter, main receiver, diversity receiver and power supplies). Apart from being the standard high-precision modulation concept of high-capacity long-haul systems, the indirect IF modulation permits some additional system features:

- The systems are prepared for an economic IF through-connection mode of operation, without regeneration modems for up to four hops, depending on the specific climatic conditions and path characteristics.
- 2-Mbit/s wayside traffic signals can be dropped from and inserted into the IF at every repeater or terminal station. The method uses reduced power IF subcarriers which are added above or below the 140-Mbit/s signal spectrum. Such subcarrier signals fit well into the excessive bandwidth of the RF channel filters.

RF channel arrangements

Fig. 2 shows the channel arrangements and relevant CCIR documents for the three frequency allocations at 2.1 GHz, 3.9 GHz and 6.2 GHz. Adjacent channels have 29-MHz, 30-MHz or 29.65-MHz spacings. They can be operated either in an interleaved pattern (IP) arrangement, with the adjacent channels mutually orthogonally polarized, or in a cochannel arrangement, in which the two polarizations of each channel frequency are used independently for the transmission of separate 140-Mbit/s bit streams, doubling the number of available RF channels. Adjacent channels are not isolated by the XPD of the antennas in this case, but by a reduced roll-off factor.

The DRS 140/2100-64 radio relay system covers the frequency band from 1900 to 2300 MHz. For this band CCIR Rec. 382 specifies six channel frequency pairs with 29-MHz spacing and a center gap of 68 MHz. Up to twelve 140-Mbit/s bit streams can be transmitted bidirectionally with cochannel operation when the center gap channels are included. Usually path planning starts with the IP arrangement and orthogonal polarization at the center gap. Then, with future capacity extensions, cochannel operation is introduced.

The DRS 140/3900-64 digital radio relay system is designed for the frequency band, 3800 MHz to 4200 MHz. CCIR Rec. 382 allocates fix frequency pairs with a 29-MHz spacing and a 68-MHz center gap. Up to twelve bidirectional 140-Mbit/s signals can be transmitted in the cochannel operation mode. The situation for center gap channel polarization is equivalent to that of the 2.1-GHz band. Additionally, in compliance with CCIR Rec. 635, in a frequency pattern with 30-MHz spacing and 60-MHz center gap ten IP channel pairs (20 cochannel pairs) are usable in the frequency band from 3.6 GHz to 4.2 GHz (or the frequency band from 3.4 GHz to 4.2 GHz on request).

The digital radio relay system, DRS 140/6200-64, can be operated in the CCIR Rec. 383 frequency pattern from 5925 MHz to 6425 MHz with 29.65-MHz channel spacing. 8 IP or 16 cochannel bidirectional 140-Mbit/s signals can be transmitted. The center gap channels, 8 and 1, being separated by only 44.5 MHz, need an excellent spectrum limitation to realize sufficient transmitter/receiver isolation. With special RF channel filters of high stability exclusively designed for these channels, they can be used on one antenna, even in the cochannel operation mode. But, due to the exceptionally small center gap spacing, channels 8 and 1 are impaired by about 1.5 dB in system gain. Basically, filter concepts, pulse shaping and the spectra of the family are designed for cochannel operation with 28-MHz channel spacing. The principal layout of the system family therefore also covers CCIR frequency allocations in the 7-GHz band (Rep. 934).

Compatibility with analog radio relay systems

In existing networks, analog radio relay systems may be operated in the RF bands at 2.1 GHz, 3.9 GHz and 6.2 GHz, transmitting TV signals or up to 1800 voice channels. During a transition period these FM radio relay systems must sometimes coexist with digital 140-Mbit/s radio relay systems on the same routes. In principle this is possible if the adjacent channel FM and digital radio relay systems are operated on different polarizations. With unfaded hop cross-polarization discrimination (XPD) values less than 28 dB, which may be expected under normal conditions, the dominant digital radio relay interference on the FM radio system remains within tolerable limits. It is advisable to investigate each hop situation individually taking into account other sources of interference and the types of equipment which have to coexist on the hop. It may be necessary to provide additional or special filters in the specific adjacent analog or digital radio relay systems. 30 pWop of interfering noise is normally well within reach.

The degradation of the digital signal under normal conditions is negligible, despite the considerably higher transmit power of the analog radio. On hops with a tendency for signal enhancement and ducting, it is advisable to transmit both the FM and adjacent digital radio relay signals from the same antenna [4]. This avoids severe XPD degradations which may occur due to fading mechanisms in connection with two transmit antennas. Usually the two antenna polarizations can easily be used for the separate operation of both types of systems on one antenna. Depending on the particular FM system it may even be possible to transmit the DRS signals on existing FM channel branching filter chains.

Facilities for assuring quality

Digital radio relay systems employed in the long-haul network are covered by the quality and availability recommendations for so-called high-grade circuits in accordance with the relevant CCITT and CCIR guidelines. If the permissible percentages for degraded minutes (BER $<10^{-6}$) and severely errored seconds ($BER < 10^{-3}$, or signal loss longer than ten consecutive seconds) are not to be exceeded, it is not enough in the case of digital radio relay systems employing multilevel modulation merely to design the system or link to provide an adequate system margin against flat fading.

The linear distortion in the transmission channel due to multipath propagation in the radio hop (multipath fading or dis-

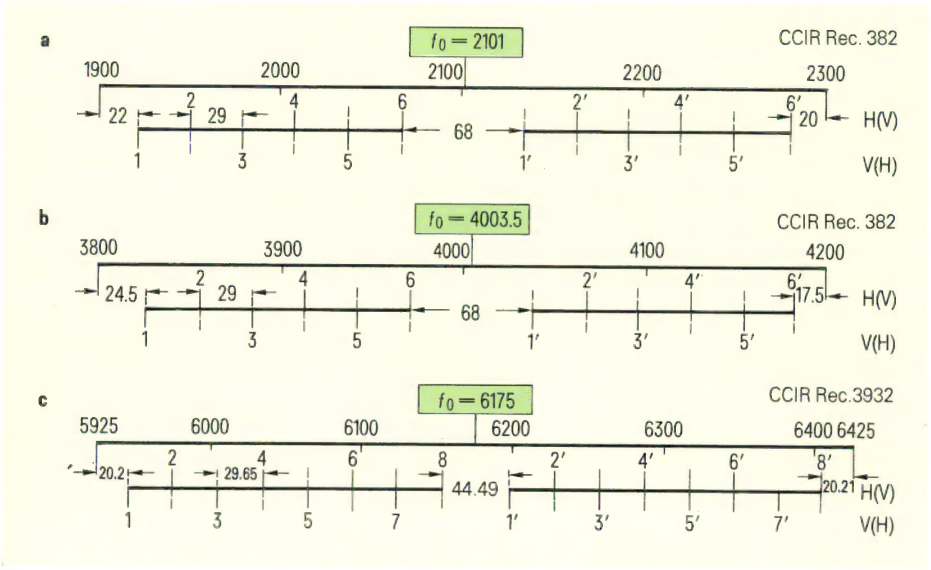
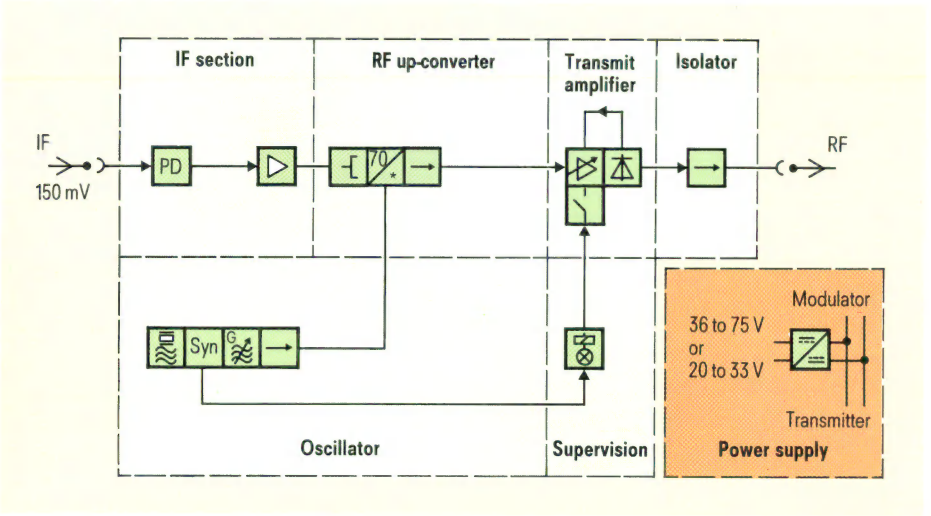


Fig. 2 RF channel arrangements for the digital radio relay systems, DRS 140/2100-64 (a), DRS 140/3900-64 (b) and DRS 140/6200-64 (c)



G Generator
IF Intermediate frequency
PD Predistorter
RF Radio frequency
Syn Synchronization

Fig. 3 Funtional diagram of the transmitter for DRS 140/2100-64, DRS 140/3900-64 and DRS 140/6200-64 digital radio relay systems

persive fading) proved to be the main cause of impaired transmission quality (with increased bit error ratios and even signal loss). To match the incidence and intensity of such propagation anomalies, additional measures, such as adaptive amplitude equalization, space diversity reception, adaptive time-domain equalizers (ATDE) and in cases of cochannel operation, cross-polarization interference cancellers are provided for the system family to assure the transmission quality.

In principal, the family concept allows for all relevant combinations of these facilities to match the requirements of specific routes and hops most economically, according to their climatic conditions, path characteristics, available capacities of towers etc.

An efficient and economic means to compensate moderate distortion is the adaptive amplitude equalizer, which is particularly effective for minimum phase distortion. It is generally used with and integrated into the adaptive time-domain equalizer (ATDE). In order to make sure that CCIR transmission quality is met with sufficient margin, it was decided to use seven-tap ATDE demodulators in general. They exhibit an exceptional ability to counter the effects of fade-related signal distortions of both types, minimum and nonminimum.

For many situations the most effective means to counteract fading due to propagation mechanisms in the stratified atmosphere is space diversity. Combining two or more signals, received from antennas at different heights (typical diversity spacing is about one hundred times the wavelength), reduces the effective fading depth of 50-km paths by typically 10 dB [4]. Moreover, path-induced amplitude and group-delay distortions can be largely eliminated. Additionally, the influence of echoes reflected from the ground is decisively diminished, due to the reduction of the fading depth [5]. Interfering signals of crossing routes at nodes are of less influence if space diversity is used.

Space diversity, used in conjunction with the ATDE demodulator, enables the relevant CCIR quality recommendations to be maintained even on hops with difficult propagation conditions. On favorable hops with moderate fading depth, however, space diversity may be dispensed with, thus reducing the cost of the radio transmission medium.

Cross-polarization interference cancellers (XPIC) are always used for 64-QAM cochannel operation. Interfering signals from the cochannel, transmitted on the other polarization, are eliminated by the XPIC in situations where the hop XPD experiences major degradation. Different conditions, such as multipath fading, echo reflections from the ground or high altitude atmospheric stratifications, and rain, can be the source of XPD degradation [5]. The ability of XPICs to counteract these types of interference is presented in [3].

System hardware

The modulation and radio sections in the family of systems presented here are realized as separate units. The DRM 140/70 modem insets described in [2] are interchangeable units common to all systems in this family. The modulator delivers an IF signal optimally filtered for the transmit-side pulse and spectrum shaping. In the transmitter, the modulated signal is translated from the IF to the RF band and amplified. In the receiver, the

modulated signal is translated from RF to IF, amplified and optimally filtered for the receive-side pulse and spectrum shaping. With 64-QAM the signal processing must introduce as little distortion as possible. Nonlinear distortion due to the modules in the signal path would otherwise produce considerable degradation of the system characteristics.

The interfaces between the modem units and the radio sections operate at the intermediate frequency of 70 MHz. The separation between radio sections and modems has advantages with regard to the stocking of spares and facilitates testing and maintenance of the equipment. The design and operation of the radio sections are described in the following paragraphs by reference to their functional diagrams.

Transmitter

As can be seen in **Fig. 3,** the transmitter inset incorporates the following functions: predistorter, IF amplifier, up-converter, carrier supply, transmit amplifier and transmitter supervision.

In order to meet the requirements for minimum nonlinear distortion with minimum loss of efficiency, the signal power at the output of the RF power amplifier is stabilized by a control circuit. A variable attenuator at the input of the RF power amplifier provides the gain control to compensate input level variations and temperature-dependent gain effects.

The 70-MHz IF signal from the modulator is fed via a PIN-diode-regulated input amplifier, the predistorter, and a special low-distortion drive amplifier to the single-sideband up-converter, which translates the IF signal to the RF band. The carrier and the unused sideband are suppressed by the up-converter in order to eliminate the need for a channel-specific sideband filter in the transmitters [6].

Frequency-stabilized and mechanically tunable microwave oscillators produce the local oscillator signal required for the conversion. The active devices employed are silicon bipolar transistors. A change of transmit frequency can be readily performed on site with the aid of the central meter.

The RF signal at the converter output is raised to the final transmit level by a transmit power amplifier which has to meet high linearity requirements. Solid-state amplifiers are employed with a nominal transmit power of 30 dBm for the 2.1-GHz band and 29 dBm for the 3.9- and the 6.2-GHz bands. They also have an output power of about 38 dBm at the 1-dB compression point. With an optional power amplifier version, 3 dB more output power is possible.

The dynamic range of the RF power amplifier and hence the available linear output power is significantly improved by compensating the nonlinear distortion by a predistorter in the IF band. A level probe monitors the power at the amplifier output. It also produces the signal for the automatic control of transmit power. If the carrier supply malfunctions (loss of synchronization), the transmit amplifier is disabled by an electronic switch to prevent the radiation of interfering signals.

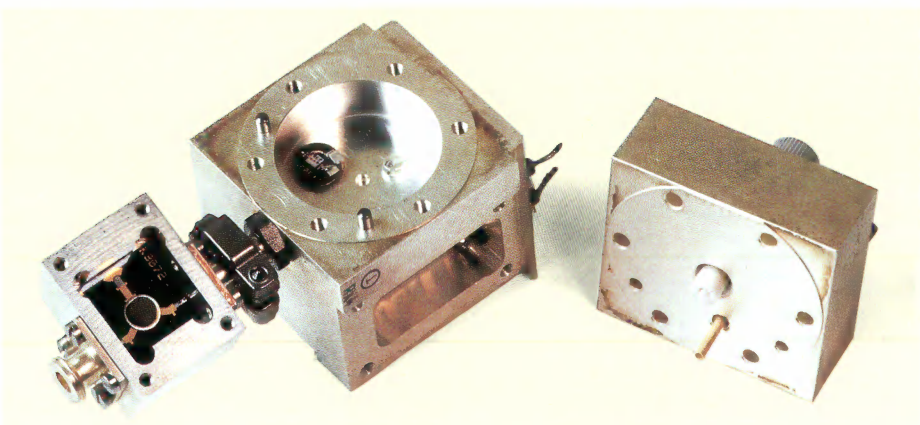


Fig. 4 RF oscillator employed in the DRS 140/6200-64 digital radio relay system

The transmit microwave oscillator of the DRS 140/6200-64 digital radio relay system shown in **Fig. 4** is a typical example of the RF modules.

Receiver

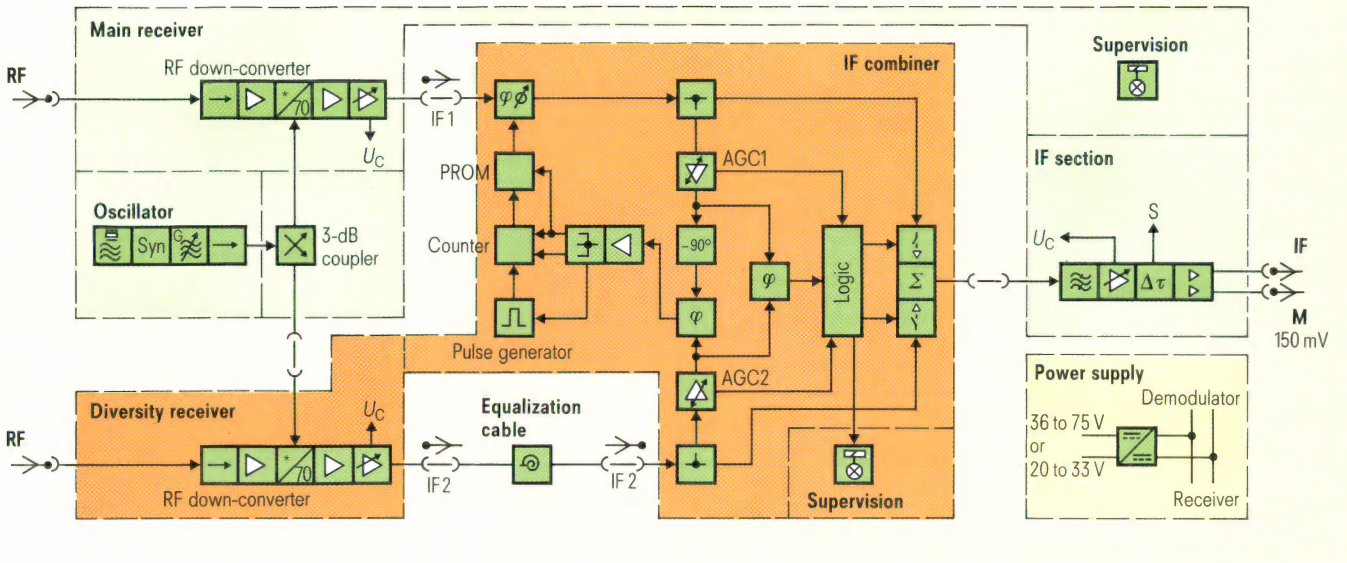
The receive side shown in **Fig. 5** comprises the two equipment insets for the main receiver and diversity receiver. The latter is required for space-diversity reception and largely eliminates the effects of selective fading by combining the two received signals.

Main receiver

The main receiver inset incorporates the functions required for single-signal reception, i.e. the RF converter, carrier supply, IF preamplifier, pulse-forming SAW IF filter, main IF amplifier and the receiver supervision circuit. Overall group delay is equalized in the SAW IF filter.

An additional group-delay equalizer can be supplied in the main IF amplifier if channel-dependent distortion is too high. The RF converter incorporates a low-noise RF preamplifier which produces an improved system gain. Translation to the IF at 70 MHz is effected with a single-sideband converter [6]. The carrier supply is similar to that in the transmitter. Cochannel operation with the use of an XPIC necessitates absolutely identical frequencies for the local oscillators of the two main receivers operating with different antenna polarizations. This is achieved by a synchronization circuit which may be added as a module to one of the receivers in the case of cochannel operation.

The local oscillator signals are available at two identical outputs for driving the down-converters of the main and diversity receivers. A low-noise, gain-controlled IF preamplifier raises the signal level and accepts high receive levels in the case of signal enhancement due to duct propagation conditions. Without space diversity, the output signal from this preamplifier is connected directly to the SAW IF filter and the main IF amplifier in the main receiver. When space diversity is used, this IF signal is fed to the IF combiner in the diversity receiver. Both requirements – a low system noise figure together with a high linearity – are met by the concept of having gain control in the IF preamplifier.



* 2100, 3900 or 6200 MHz
AGC Automatic gain control
φ Phase comparator
$\varphi\varnothing$ Endless phase shifter
G Generator
IF Intermediate frequency
M IF test output
RF Radio frequency
S Supervision
Syn Synchronization
U_C Control voltage

Fig. 5 Functional diagram of the space diversity receive system for DRS 140/2100-64, DRS 140/3900-64 and DRS 140/6200-64 digital radio relay systems

The SAW IF filter has to fulfill several tasks: it must suppress adjacent channel signals, establish the exact roll-off factor ($\varrho = 0.45$ or $\varrho = 0.25$) for optimal demodulation, act as a pulse-forming network, and equalize the overall group-delay distortion of the system RF and IF filters. The gain-controlled main IF amplifier operates in conjunction with the IF preamplifier to raise the level to a constant value at the output, provided that the receive level is within its control range. The IF transfer level to the following demodulator is generated with low distortion by very linear IF output stages.

Diversity receiver

The diversity receiver contains an RF converter module, which is identical to that of the main receiver. It also contains a diversity combiner which operates in the IF band.

The receive signal from the diversity antenna is mixed with the local oscillator signal, which is generated in the main receiver, and is connected to the diversity receiver to ensure that the resultant IF signal is of exactly the same frequency as the IF signal obtained from the main receiver. The signal is then amplified in the IF preamplifier which has the same gain as the IF preamplifier in the main receiver. The same AGC voltage that is derived from the IF main amplifier in the main receiver controls the gains of both preamplifiers.

The signals from the outputs of both IF preamplifiers are added in phase in the IF combiner (maximum power or in-phase combiner). The signal derived from the antenna with the shorter length of antenna feeder is passed through an equalizing line to compensate the delay difference due to the differing lengths of the antenna feeders. This line is accommodated in its own small inset in the receiver rack.

The second IF branch of the combiner (**Fig. 5**) incorporates an endless phase shifter which is adjusted digitally via a phase-locked loop to ensure that the signals from the main and diversity antennas are added in phase in the summing network. In order to compare the phases of the two channels in an analog phase detector, signal samples are extracted and each of these is raised to a constant level in a gain-controlled amplifier.

The two branches are monitored for level differences via the AGC voltages of the two gain-controlled amplifiers. If the difference exceeds 10 dB, the branch with the lower (less favorable) level can be electronically disconnected. It is not necessary to assign the two receive branches to the antennas according to the differing feeder lengths, since the delay equalizing line can be assigned within the unit. Level differences between the two branches due to differing antenna sizes, for instance, can also be equalized.

Equipment power supply

The transmit and receive sides are each assigned separate but identical power supply insets designed for operation from battery supplies ranging from 36 to 75 V (floating) or 20 to 33 V (optional). The operating voltages which they provide for the equipment insets are short-circuitproof and isolated from the primary side. The modulator and demodulator insets are also operated from the power supplies. A special pin-compatible version of the transmitter power supply is available for the transmitter option with 3 dB higher output power.

System supervision

The supervision modules are accommodatd in the transmitter and receiver insets. Any faults are indicated by LEDs in the defective inset and by passing on a fault signal. The fault signals on the transmit side are:

- loss of baseband signal at the modulator input (MS1),
- loss of frame clock and data in the modulator (MS2),

- loss of IF signal at the modulator output (MS2),
- loss of synchronization in the carrier supply (MS2),
- loss of transmitter output power (MS2),
- other equipment faults, e.g. voltage failure (MS2),

On the receive side they are:

- loss of channel identification or inadequate transmission quality (ML),
- loss of synchronization in the carrier supply (ME),
- loss of synchronization between two carrier supplies during cochannel operation (ME),
- loss of IF input level at the demodulator, loss of frame clock (ME),
- other equipment faults (ME), e.g. voltage failure,
- IF combiner failure (ME).

The fault signals, MS1 and MS2 as well as ML and ME, are passed to a remote supervision facility via isolating contacts; they are also used as switching criteria for a protection-switching equipment. Faults which result in the interruption of the wanted signal initiate an alarm signal and are indicated visually and audibly in the rack frame.

For fault location purposes, a centrally located meter is provided in the rack configuration and can be connected via multi-contact jacks to the system insets. If a transmitter or receiver inset has to be replaced, local oscillators can be easily adjusted by using this central meter.

The main receiver has a recorder output for the sum receive level, and the diversity receiver has a recorder output for the difference in receive levels between the two branches.

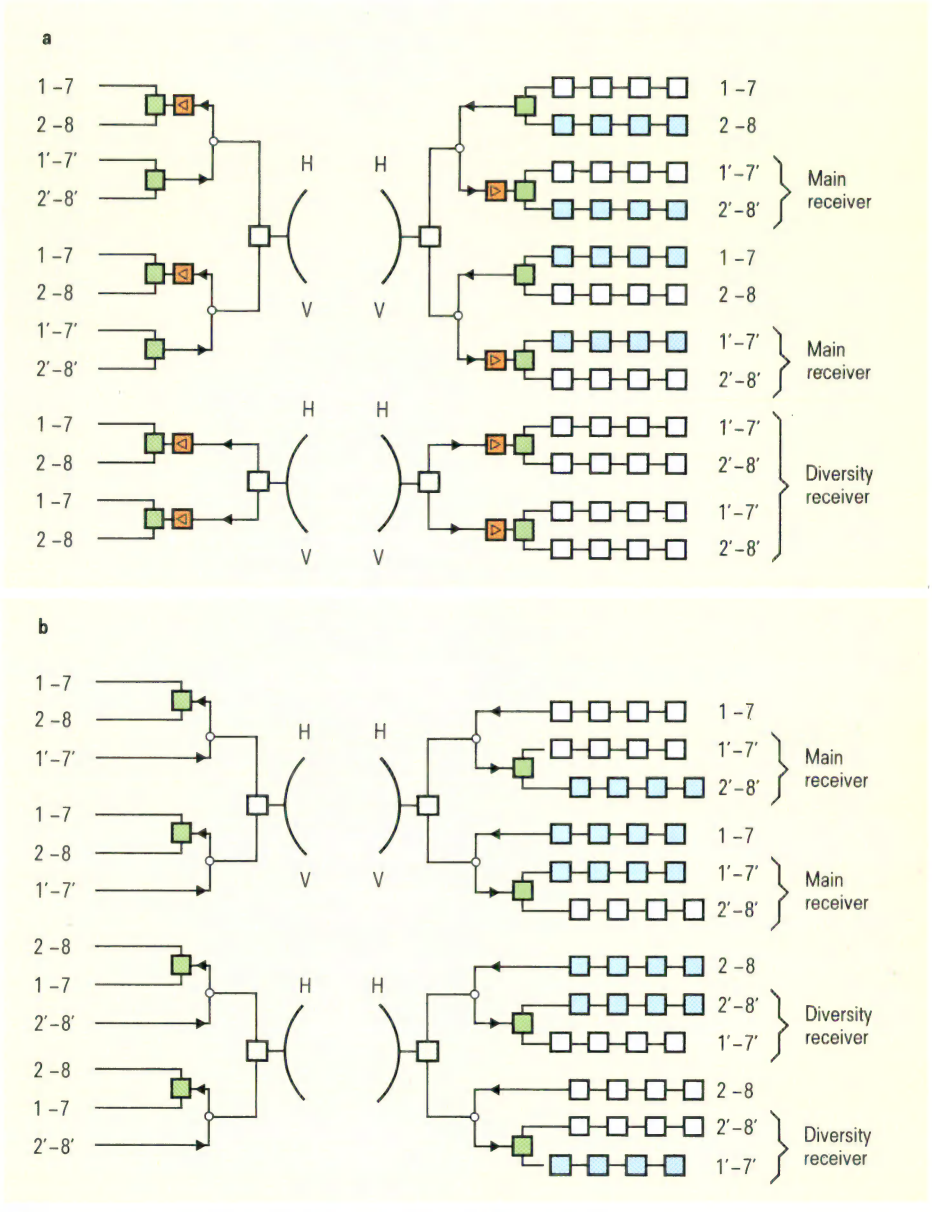


Fig. 6 RF channel/antenna arrangements for interleaved pattern and cochannel transmission
a Co- and adjacent channel transmitters on the same antenna
b Cochannel transmitters on the same antenna, adjacent channel transmitters on different antennas

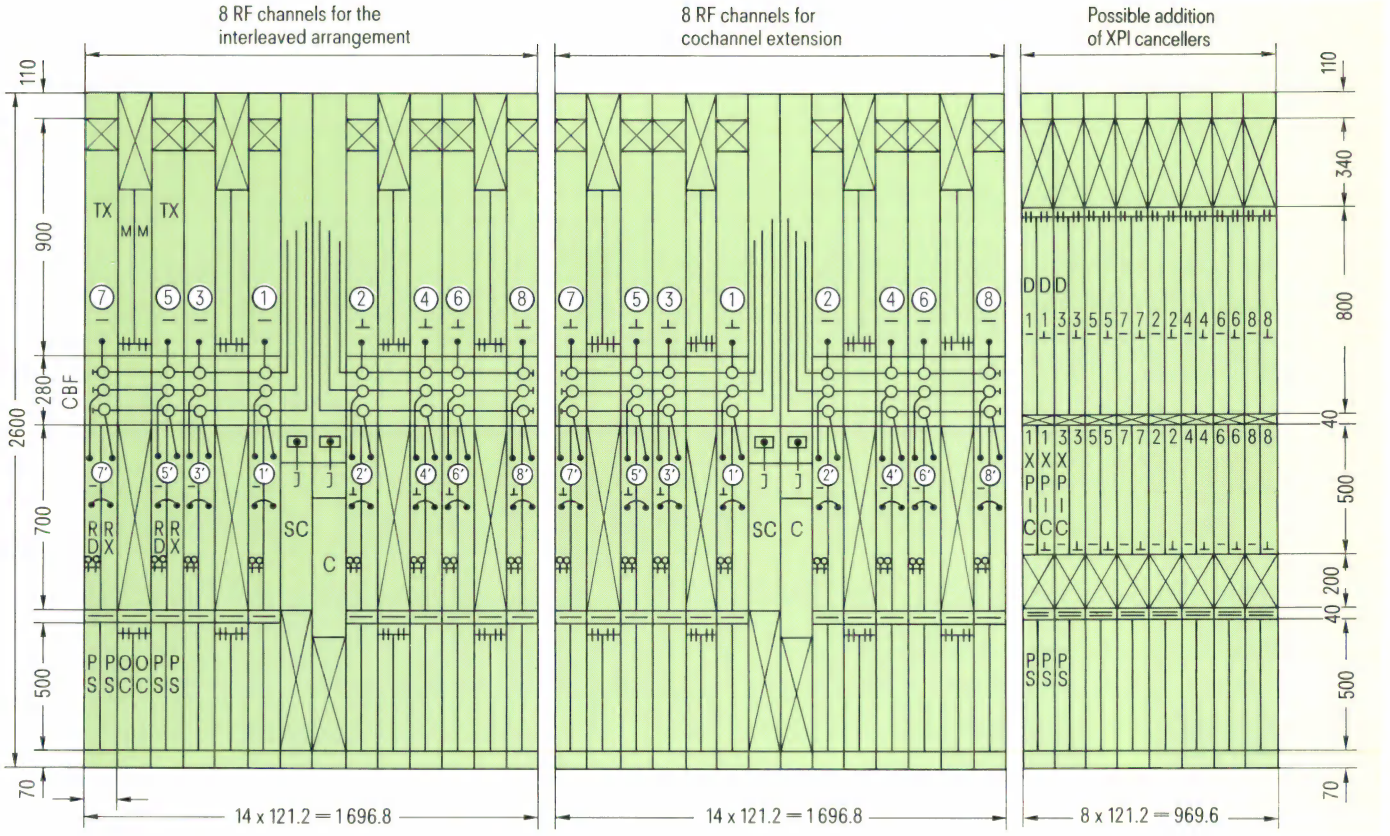
Channel branching filters and connection to antenna

The channel branching filters on both the transmit and receive sides consists of six-section filters with attenuation poles. They are designed with coaxial resonators for the 2.1-GHz and 3.9-GHz bands, but with cavity resonators for the 6.2-GHz band. The filters have coaxial connectors and are identical for the transmit side and both receivers. Transmit and receive channel branching filter chains (formed by circulators and channel branching filters [7]) are coupled via a transmit/receive circulator and are connected via a common waveguide feeder to one of the polarization planes of the antenna. For the diversity receive branch, a separate branching filter chain similar to those of the transmit and main receive branches is required. A filter inserted after each of the transmit filter chains suppresses harmonics of the transmit signals.

Depending on the frequency band, up to five branching filters are connected to a branching filter arrangement for the DRS 140/3900 system, whereas a maximum of three or four filters are provided in the DRS 140/2100 and DRS 140/6200 systems, respectively.

Existing radio towers often have a limited capacity as far as the number of antennas is concerned. Solutions must therefore be chosen which transmit all RF channel pairs using only one antenna without space diversity, or using two antennas in cases where space diversity is unavoidable.

Three possibilities are available, each with different advantages. The only difference between them is whether the cochannel transmitters and the adjacent channel transmitters are arranged on the same antenna or on separate ones.



C	(1+1) control inset	OC	Operating channel	SW	Switching inset
CBF	Channel branching filter arrangement	PS	Power supply	TX	Transmitter
D	Demodulator	RX	Receiver	XPIC	Cross-polarization interference canceler
J	Meter	RD	Diversity receiver	⊥	Vertical } polarization
M	Modulator	SC	Service channel inset	—	Horizontal } polarization

(dimensions in mm)

Fig. 7 Rack configuration for the family of radio relay systems DRS 140/3900, 4700, 6700, 11200, 13000 and 15000

Selection of an appropriate RF channel/antenna arrangement (**Fig. 6**) – out of the three possibilities – depends on the extent to which the paths are prone to ducting and signal enhancement. The solution presented in **Fig. 6a,** with co- and adjacent-channel transmitters connected to the same antenna, is especially suitable for hops with a tendency for duct propagation and signal enhancement. Furthermore, this arrangement preserves valuable tower capacity for future expansion of transmission capacity and makes efficient use of antennas. More details are presented in [4].

Mechanical design

Three style 7R racks located side by side can accommodate – in the same configuration for all three radio frequency bands – two transmitters and two receivers (including diversity) with the associated modem and power supply insets and the insets of the (1+1) protection-switching units (**Fig. 7**). Full expansion to 16 RF channels in the 6.2-GHz band with the addition of the XPICs is also shown in **Fig. 7.** The transmit and receive sides are each assigned separate power supplies which are located side by side in the lower section of the rack. These supplies also serve the system modulator and demodulator units, which are mounted in an unwired empty rack between the two radio racks. On radio relay links with protection switching, the insets providing the (1+1) switching facility are mounted in the same rack as the modulators and demodulators. The switching and control insets of an (N+1) protection-switching equipment can either be integrated in the system configuration or grouped in separate switching racks [3]. The terminal panel of the radio rack is the point of concentration for all the connections leading from the radio relay units to the outside.

Cochannel operation should always be a safeguarding option for future route capacity extensions. No preinvestment or preinstallation is required for future expansion with cochannel operation. The rack layout for cochannel operation is based on this concept. It is possible to start with the normal rack arrangement for 8 RF channels in interleaved patterns. When it becomes necessary to extend the route capacity by cochannel operation, cochannel racks may be added, channel by channel, in an identical rack arrangement. In cases where it subsequently proves necessary to add XPICs, it is possible to add them in special racks, which may be up to 10 m from the radio racks.

System data

The **Table** summarizes the principal data of all three members of the system family. It is possible to get a fading margin of 35 dB for all systems if high-performance antennas and low attenuation antenna feeders are used. The **Table** also lists available antennas which could be employed in these systems. Essential data are high gain to get a high fading margin, and high front-to-back ratios to avoid interference from transmitters operating on the same radio frequency in the next hop in case of deep fading.

Digital radio relay systems	DRS 140/2100-64	DRS 140/3900-64		DRS 140/6200-64
General data				
Frequency range	1900 to 2300 MHz	3800 to 4200 MHz	3600 to 4200 MHz	5925 to 6425 MHz
Modulation	64 QAM	64 QAM		64 QAM
Number of possible RF channel pairs				
interleaved pattern	6	6	10	8
cochannel operation	12	12	20	16
Minimum channel spacing on a channel branching filter	58 MHz	29 MHz	30 MHz	59.3 MHz
Transmission capacity	139.264 Mbit/s	139.264 Mbit/s		139.264 Mbit/s
Center gap spacing	68 MHz	68 MHz	60 MHz	44.49 MHz
Transmitter				
Transmit power (mean)	30 (33)* dBm	29 (32)* dBm		29 (32)* dBm
Intermediate frequency	140 MHz	140 MHz		140 MHz
Transmit frequency drift	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$		$7 \cdot 10^{-6}$
Receiver				
RF input power	−38 dBm	−37 dBm		−37 dBm
Permissible control range of receive power	−15 to −78 dBm	−15 to −78 dBm		−15 to −78 dBm
Noise figure (typical)	3 dB	4 dB		4 dB
Minimum receive power for 10^{-3} BER (typical)	−73 dBm	−72 dBm		−72 dBm
Oscillator frequency drift	$7 \cdot 10^{-6}$	$7 \cdot 10^{-6}$		$7 \cdot 10^{-6}$
System gain (minimum) (10^{-3} BER)	103 (106)* dB	101 (104)* dB		101 (104)* dB
Power supply				
Battery voltage	20 to 33 V or 36 to 75 V	22 to 33 V or 36 to 75 V		20 to 33 V or 36 to 75 V
Digital service channels	Omnibus channel (1 × 138 kbit/s) Express channels (2 × 138 kbit/s and 3 × 34.5 kbit/s)			

Antennas	4 m Parabolic	3 m Parabolic	3 m Shell	4 m Parabolic	3 m Parabolic	3 m Shell	4 m Parabolic	3 m Parabolic
Frequency	2100 MHz			3900 MHz			6200 MHz	
Gain (center of band)	35.9 dB	33.4 dB	39.0 dB	41.3 dB	38.8 dB	43.1 dB	45.4 dB	42.9 dB
Front-to-back ratio	65 dB	65 dB	70 dB	70 dB	70 dB	70 dB	70 dB	70 dB

* Optional

Table Technical specifications of the digital radio relay systems, DRS 140/2100-64, DRS 140/3900-64 and DRS 140/6200-64

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Klaus Otremba, Jan Steinkamp, Hans-Jörg Thaler and Klaus Vogel

High-Capacity Digital Radio Relay System Family for the 18-GHz Band

A new, high capacity radio system family for the 18-GHz band has been designed for use in local and regional networks. The main applications of this system family are: extension of optical fiber routes to downtown communication centers and facilitating frequency coordination in densely meshed trunk radio networks in conurbations. The system was therefore designed to have a high spectrum efficiency of up to 6.8 bit/s/Hz and to be highly economical. In order to achieve high transmission capacity, 16-QAM and cochannel operation are used enabling a maximum of 4 × 140 Mbit/s (or 12 × 45 Mbit/s) to be transmitted via one RF with 110-MHz or 80-MHz channel spacing, respectively. For cochannel operation a cross-polarization interference canceller (XPIC) may be used to compensate for the depolarization effects of rain. There are two basic system versions: one for indoor installation making use of low-loss overmoded waveguide feeders and one for outdoor mounting in weatherproof casings near the antenna.

In this article a discussion of the scope of the new system family is followed by a review of the channel allocation plans for the 18-GHz band. Basic system considerations such as modulation format, spectrum shaping and RF concept are then treated together with system planning aspects in connection with rain attenuation and depolarization. The electrical and mechanical system layout is described, special attention being given to the applied RF technology.

The article concludes by considering system applications for long-haul trunk extensions and local connections and by examining the relationship between availability, rain climate conditions, the required system margin and possible hop length.

Introduction

Short-haul, high-capacity digital radio links operating in the 18-GHz band (17.7 to 19.7 GHz) have to meet special requirements with respect to flexibility and economy on the one hand and to transmission capacity and system availability on the other. A certain duality is apparent here in that route extension radio links for the trunk network must meet high grade performance objectives, while local network links only have to fulfill medium grade performance specifications. In the latter case the emphasis is placed on cost effectiveness. These requirements – in some respects contradictory – are met by adhering strictly to a modular system concept which allows the optimal combination of a number of different modules for the particular application. Furthermore, the modular concept enables system versions to be set up easily for indoor and outdoor installations and for different fade margin requirements.

The system layout features optimum interfaces to trunk routes operating in lower frequency bands – either to fiber optic systems or to wideband radio relay trunk routes. System versions can therefore transmit 1 × 140 Mbit/s signal as well as two plesiochronous 140-Mbit/s signals; if cochannel operation is used, a 4 × 140 Mbit/s CEPT interface can be included. For the USA hierarchy, up to 12 × DS3 plesiochronous interfaces are available at the input and output of the two transmitter/receiver sets operating at one RF in both polarizations.

Frequency allocations in the 18-GHz band

For the RF band from 17700 MHz to 19700 MHz, two different allocation plans have been standardized, one recommended by the CCIR (Rec. 595) and adopted by the CEPT and one worked out by the FCC (FCC Docket 83/188) for use in the USA. Since not only the structure but also the channel spacings in both plans are different, specific system development measures are necessary to fully utilize the potential of both plans.

The basic structure of the RF channel allocation plan based on CCIR Rec. 595 with a channel spacing of 220 MHz, a transmitter-receiver frequency separation of 1120 MHz and a center gap of 460 MHz for 4 RF channel pairs is shown in **Fig. 1a.** This basic structure was modified in order to achieve a more efficient spectrum utilization; the resulting allocation plan has 110-MHz channel spacing, 1010-MHz transmitter-receiver spacing and a center gap of 240 MHz, yielding a total of eight RF channel pairs (**Fig. 1b**). For 34-Mbit/s systems using QPSK or 4FSK, the Deutsche Bundespost has introduced a variant of this 110-MHz allocation plan providing 35 RF channel pairs with 27.5-MHz chan-

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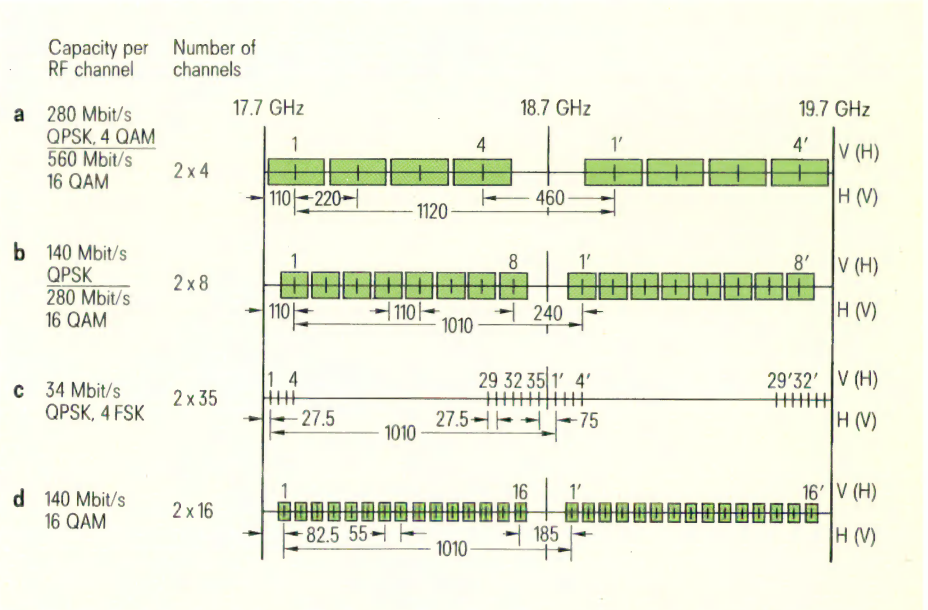
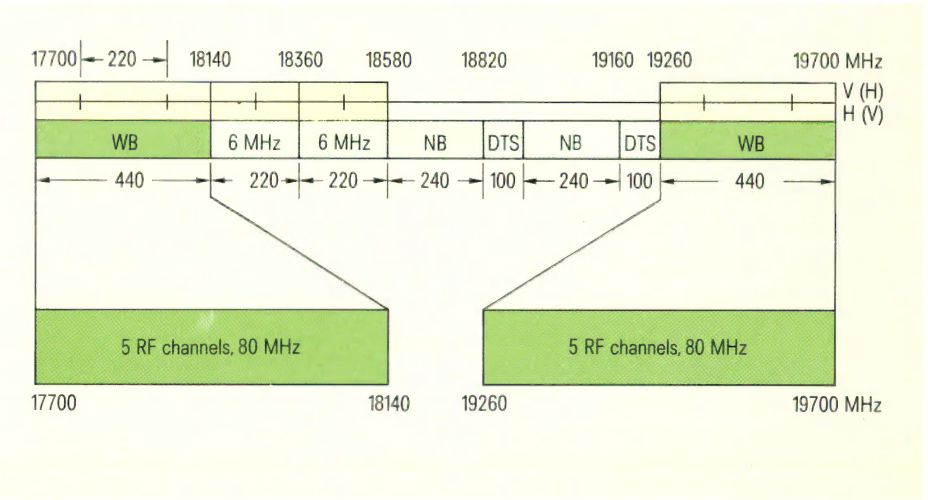
nel spacing and the same transmitter-receiver spacing of 1010 MHz. This variant (**Fig. 1c**) is used to derive an RF channel allocation plan for 16 RF channel pairs with 55-MHz channel spacing, a center gap of 185 MHz and the same transmitter-receiver spacing of 1010 MHz. This plan (**Fig. 1d**) provides a sufficient number of RF channels to facilitate frequency coordination in conurbations and, at the same time, employs a channel spacing of 55 MHz to provide good spectrum utilization with 16-QAM systems and cochannel operation with moderate roll-off factors. For both allocation plans the maximum band capacity for two-way traffic is 4480 Mbit/s.

Fig. 2 shows the RF allocation plan standardized by the FCC: a greatly modified version of the original basic 220 MHz structure of the CCIR. The two wideband (WB) sections from 17.70 GHz to 18.14 GHz and 19.26 GHz to 19.70 GHz are planned for high-capacity applications. Each can provide five RF channels with 80-MHz channel spacing. This allocation plan is also well suited for 16-QAM systems if a smaller roll-off factor is used, as shown in **Table 1**. The band capacity for the two wideband sections provides a maximum band capacity of 2700 Mbit/s for cochannel operation and two-way traffic.



QPSK Quaternary phase shift keying
RF Radio frequency

Fig. 1 RF channel allocation plan for the 18-GHz band based on CCIR Rec. 595



DTS Digital termination system
NB 5-, 10- and 20-MHz channels
WB 10-, 20-, 40- and 80-MHz channels
RF Radio frequency

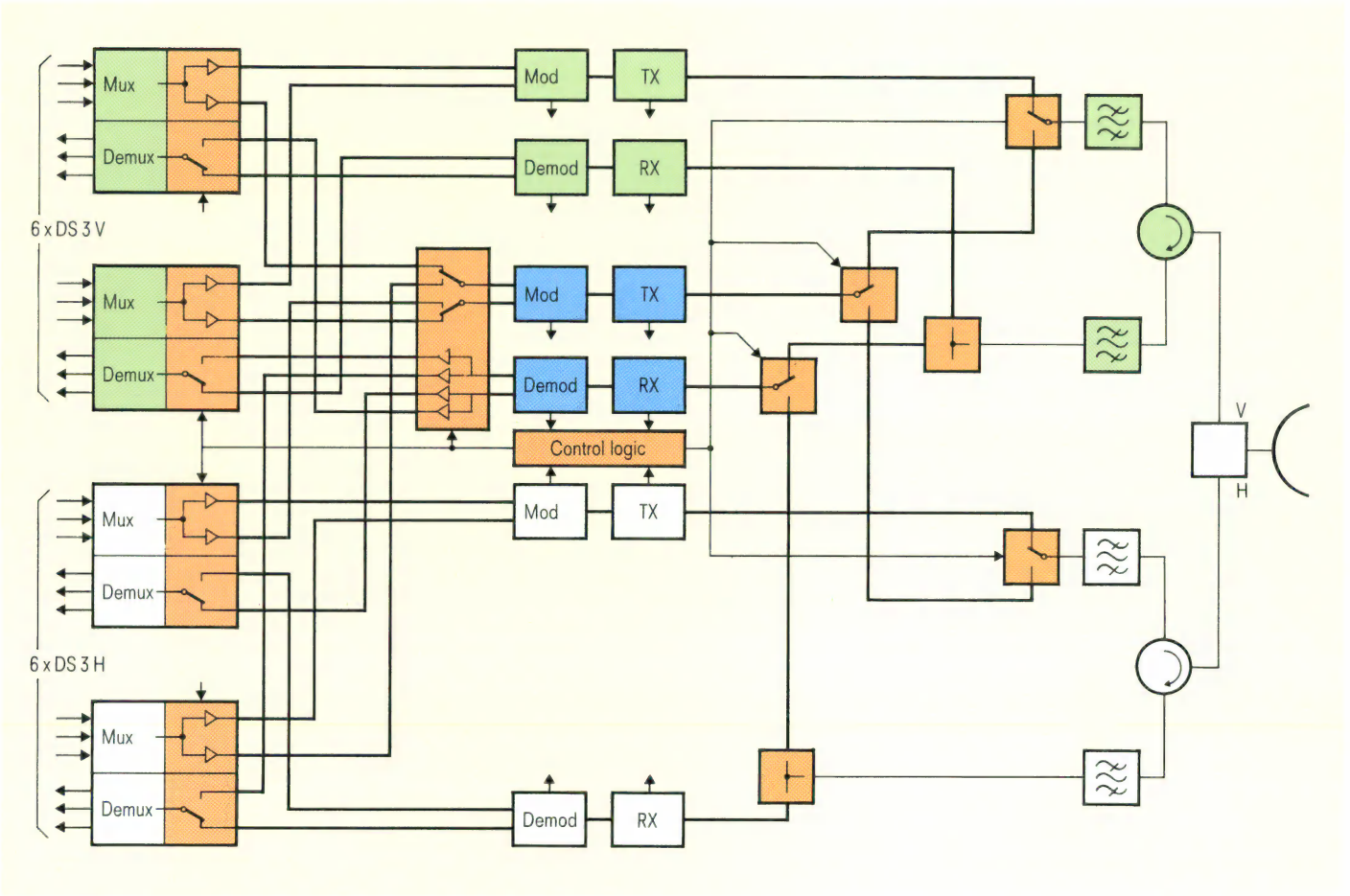
Fig. 2 FCC RF channel allocation plan

Basic system considerations

Since the RF allocation plans discussed above enable a variety of system versions to be designed for different channel spacings (bearing in mind the required high spectrum efficiency), direct modulation of the RF carrier is not appropriate. Therefore, indirect modulation at an IF of 140 MHz and quadrature amplitude modulation (QAM) with a different number of states are used for the 18-MHz system family. The systems were designed in accordance with the CCIR and CEPT recommendations for the CCIR and FCC frequency patterns presented above. Four-state quadrature amplitude modulation (4 QAM) has proven to be an economic and very robust modulation scheme that is highly insensitive to noise and interference. 16 QAM has been chosen for applications where band efficiency and a large number of available RF channels are essential for the

CCIR/CEPT	Modulation scheme	Available RF-channel pairs		Channel spacing	Roll-off factor
		Cochannel arrangement	Interleaved channel arrangement		
DRS 140/18700/4	4 QAM	16	8	110 MHz	0.5
DRS 140/18700/16	16 QAM	32	16	55 MHz	0.5
DRS 2 × 140/18700/16	16 QAM	16	8	110 MHz	0.5
FCC					
DRS 3 × DS3/18700/16	16 QAM	10	5	40 MHz	0.2
DRS 6 × DS3/18700/16	16 QAM	10	5	80 MHz	0.2

Table 1 Characteristics of 18-GHz system versions for operation according to CCIR/CEPT and FCC recommendations



RX Receiver
TX Transmitter

Fig. 3 2 + 1 hot standby configuration with cochannel operation

realization of densely meshed networks, e.g. 1 × 140 Mbit/s with 55-MHz channel spacing. Using 16 QAM for the transmission of 2 × 140 Mbit/s or 6 × DS3 bitstreams results in a major improvement of the radio cost effectiveness and in high band efficiency in the recommended patterns with 110-MHz and 80-MHz spacing.

The pulse and spectrum shaping roll-off filters are generally implemented in the IF with surface acoustic wave (SAW) filter modules, which are different but pin-compatible [1]. As such, they are easily interchangeable. The use of this advanced technology is a prerequisite for cochannel operation. The two orthogonal polarizations can be used independently for each radio frequency.

This means a doubling of the number of RF channels available with the interleaved channel arrangement and raises the spectrum efficiency to 6.8 bit/s/Hz. In addition, this feature results in a considerably more economic utilization of the existing infrastructure (roads, buildings, towers, etc.). The particularly high adjacent channel isolation of the cochannel systems due to their extremely good spectrum confinement can be exploited for frequency coordination in densely meshed networks, in this way maintaining the maximum capacity of the radio networks for future capacity extensions. Finally, the reduced transmit spectrum bandwidth may often provide a solution to coexistence problems between networks of different carriers.

The cochannel feature also represents a safeguarding option which is exploited for radio routes with interleaved channel arrangements if the network at a later date requires increased capacity and has to be extended to cochannel operation. Such an option does not incur any pre-investment or preinstallation. In such cases, a cross-polarization interference canceller (XPIC) can be implemented. Whether or not XPICs are necessary depends to a very large extent on radio path conditions.

Different system versions are available (or in preparation) for the different RF channel allocation plans, channel spacing and hierarchies. The different versions which adher strictly to a modular family concept are listed in the system matrix in **Table 1**.

Because path lengths are generally short and dispersive fading effects are negligible, space diversity is not necessary in the 18-GHz band. Therefore, all RF channel pairs in an interleaved channel arrangement can be transmitted via one antenna. A second antenna must be used if cochannel operation is employed to double the system capacity.

The transition from an interleaved RF channel/antenna arrangement to a cochannel arrangement can be carried out in different ways to suit local conditions. For example, the link could be installed to operate with an interleaved pattern, using first one polarization plane and afterwards the second. To extend the route capacity by using cochannel operation, a second antenna

would have to be installed also using both polarizations.

One advantage of the system concept described is that different system versions can coexist on the same antenna. This is possible because the channel branching filters for all versions have identical mechanical outlines and interfaces. In addition, the family concept offers some additional features:

- The systems allow IF through-connection. This means that operation over several hops is possible without regenerating modems, the actual number of hops being dependent on the climatic conditions and the path characteristics. Radio link economy is thus improved.
- 2-Mbit/s wayside traffic signals can be dropped from and inserted into the IF signal path at every repeater station or terminal station. This method employs IF subcarriers which are added above or below the 140-Mbit/s signal spectrum and fit well into the bandwidth of the RF channel filters.
- Modular system options such as a low-noise RF preamplifier and GaAs FET (or traveling-wave tube) power amplifiers with and without predistortion allow for a large system gain range (e.g. 88 dB to 108 dB for DRS 140/18700/16 QAM). It is thus possible to flexibly and economically adapt the system to the specific requirements of a radio hop.
- The supervision method used complies with the performance requirements of high grade trunk routes and is based on the use of a signal format with a radio frame and parity bit error detection [2].
- The protection switching equipment employs either standard ($N + 1$) or ($1 + 1$) hitless configurations [3]. For equipment protection with cochannel operation, however, a special, highly cost-effective ($2 + 1$) hot standby configuration has been designed (**Fig. 3**). In this case the protection channel is utilized for both polarization planes by means of electronic switches in front of the transmit filter chain and behind the receive filter chain. The major advantage of this configuration is that two operating channels use one protection channel operating on the same radio frequency – a highly economic solution.

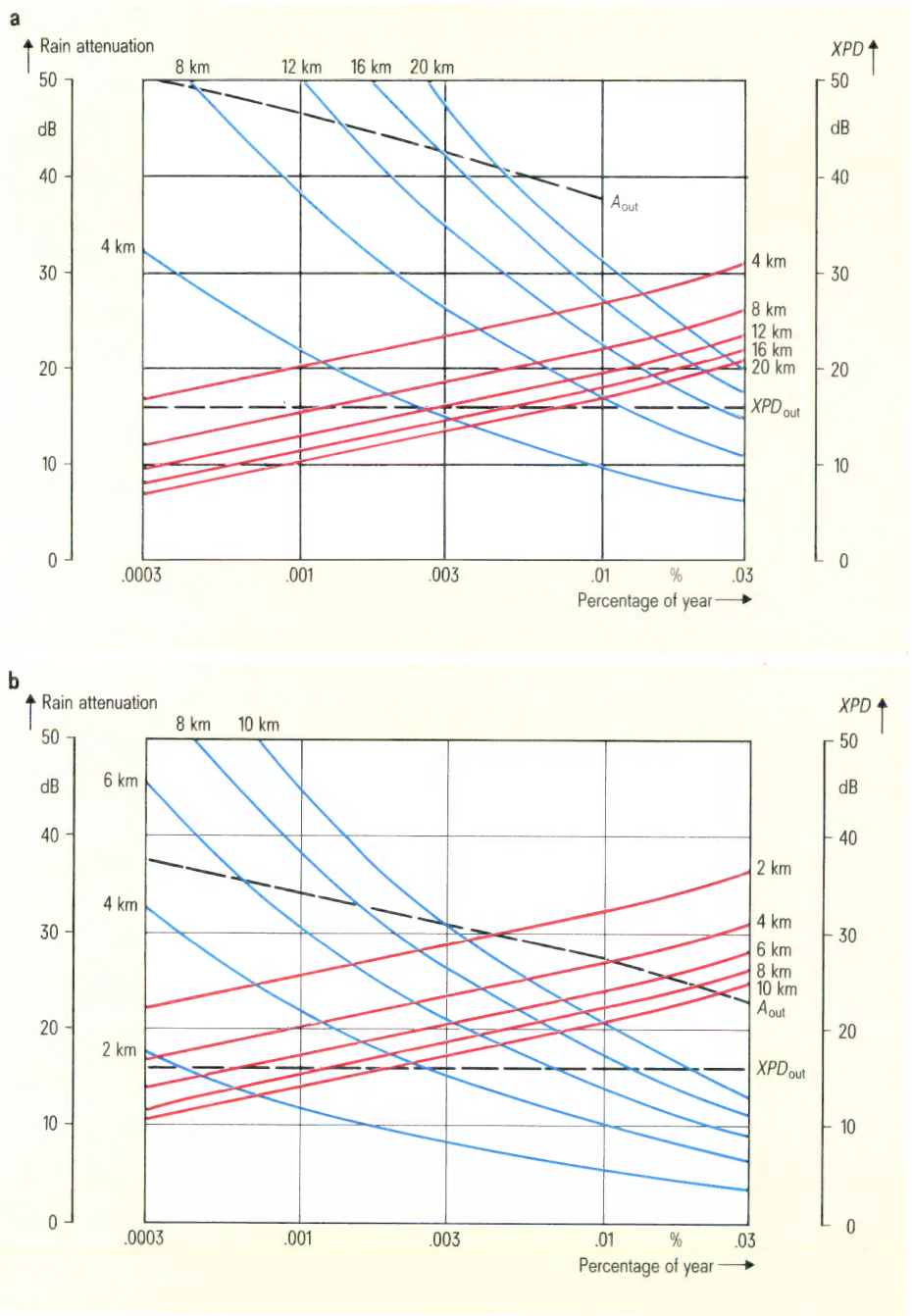


Fig. 4 **Rain attenuation and *XPD* versus percentage of year, with hop length as a parameter**

a A_{out} **1 km = 51 dB (0.05 W, 1.2 m)**
XPD_{out} **16 QAM = 16 dB**

b A_{out} **1 km = 67 dB (2 W, 1.2 m)**
XPD_{out} **16 QAM = 16 dB**

System Planning

The transmission performance of radio relay links operating in the 18-GHz band is mainly affected by precipitation (rain), induced attenuation and depolarization. Since rainfall resulting in additional signal attenuation large enough to cause unacceptable bit error ratios ($BER > 10^{-3}$ or severly errored seconds, SES) normally lasts longer than ten seconds, the main impairment is the percentage of time during which the link is not available (unavailable seconds, UAS). The other transmission quality objectives such as errored seconds (ES),

degraded minutes (DM, $BER > 10^{-6}$), severly errored seconds (SES, $BER > 10^{-3}$) turn out to be less critical. It is generally sufficient if the design of 18-GHz radio links only takes into account the permitted unavailable time resulting from rain attenuation. Multipath fading over the maximum hop length does not normally play a significant role.

The probability distribution of rain attenuation values for a radio link is derived from known (or assumed) point rain rate statistics following the procedures given in CCIR Reports 338 and 721. Local rain climates are characterized by the point rain rate $R_{0.01\%}$ (in mm/h) exceeded 0.01% of the time of the year. The effects of hop length, limited rain cell size and polarization must be taken into consideration.

The precipitation induced degradation of cross polar discrimination on a hop (XPD_{HOP}) is directly related to the rain attenuation (A). For planning purposes the relationship between the most probable XPD and A is assumed to be that given in CCIR Report 338 [1].

General:

$$XPD_{HOP} = 15 + 30 \log f\,(\text{GHz}) - 20 \log A\,(\text{dB}),\ (\text{dB})$$

18.7 GHz:

$$XPD_{HOP} = 53 - 20 \log A\,(\text{dB}),\ (\text{dB})$$

When considering outages the XPD contributions from the antennas are negligible; they only limit the overal XPD if XPD_{HOP} is large (for small A).

In **Figs. 4a** and **4b**, the exceeded rain attenuation values are plotted against the percentage of the time of a year. The values shown are for hop lengths of 2, 4, 6, 8 and 10 km (and 4, 8, 12, 16 and 20 km, respectively) and a moderate European climate characterized by an $R_{0.01\%}$ of 32 mm/h. Two different transmit power levels for a 16-QAM system carrying 2 × 140 Mbit/s are considered:

- 0.05 W (= 17 dBm) and
- 2.0 W (= 33 dBm),

resulting in 1-km fade margins ($A_{1\text{-km}}$) of 51 and 67 dB, respectively.

The dashed lines in **Figs. 4a** and **4b** represent the maximum tolerable values for rain attenuation (A_{OUT}), which decreases with hop length, and XPD_{OUT} (16 dB is assumed for 16 QAM). The intersection points of the curves with the rain attenuation (or XPD) characteristics define the unavailability for a given hop length. An increase of the system fade margin by 16 dB (**Figs. 4a** and **4b**) results in an increase of the hop length by a factor of about 1.6.

For the system configuration with a 1 km fade margin of 67 dB, unavailability (expressed as a percentage of time resulting from $XPD_{HOP} < XPD_{OUT}$) is larger than that resulting from $A > A_{OUT}$.

Example

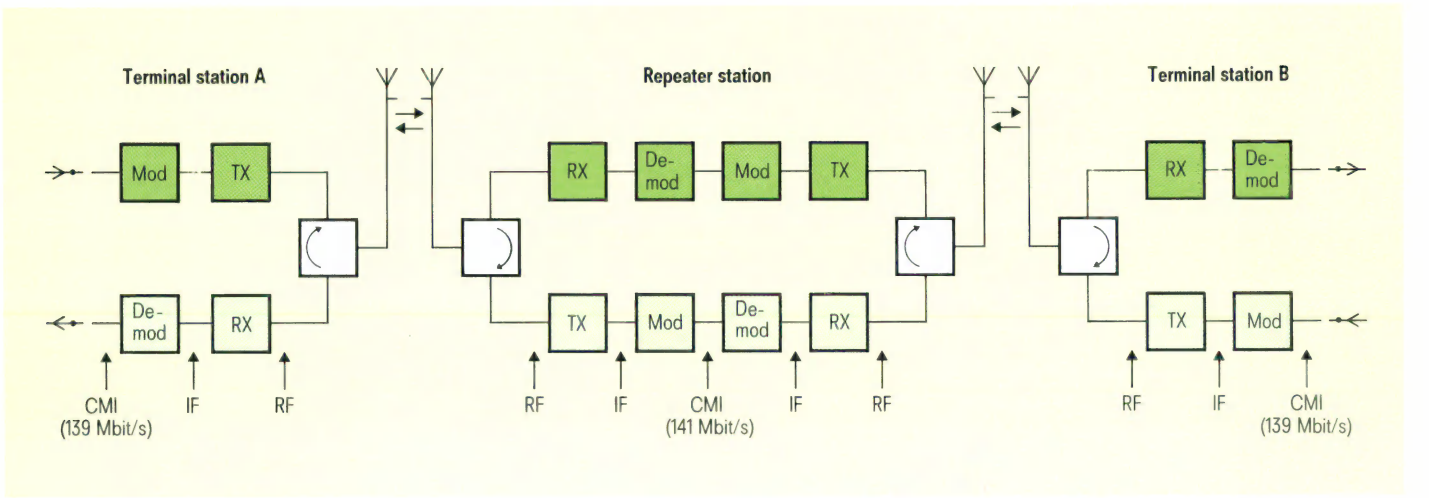
$d = 12$ km: $XPD_{OUT} \rightarrow 0.0027\%$, $A_{OUT} \rightarrow 0.0013\%$.

In this case the system availability is XPD-limited. To overcome this limitation a cross-polarization interference canceller (XPIC) is necessary to make full use of the large fade margin provided [2].

The hop length which can be achieved with 18-GHz radio links mainly depends on the distribution of the local rain intensity and the actual unavailability allowed for the links. A straightforward allocation proportional to hop length (e.g. 0.3%/2500 km), as used for long-haul high grade links, would severely limit the applications of 18-GHz radio links, particularly in trunk networks and in areas with high precipitation activity.

It would seem reasonable therefore to allocate a larger portion of the total unavailability (e.g. that for an entire high grade switching section) to 18-GHz radio links, irrespective of the actual length of the link.

The CCITT and CCIR have not yet established applicable medium grade unavailability objectives for regional and local networks. Administrations generally use individual values based on their network models. Values between 0.001 and 0.01% per year allow maximum radio spans ranging from 7 km to 20 km for an $R_{0.01\%}$ of 32 mm/h and from 3.5 km to 7 km for an $R_{0.01\%}$ of 63 mm/h (for P_T of 17 dBm). These data show that the different system configurations presented are effective for transmission applications in trunk, regional and local networks.



CMI Coded mark inversion
IF Intermediate frequency
Mod Modulator
RF Radio frequency
RX Receiver
TX Transmitter

Fig. 5 Block diagram of a wideband digital radio relay link

System description of the DRS 140/18700

Electrical design

The block diagram in **Fig. 5** represents a typical wideband digital radio relay link. As described in [2], modulation and demodulation are performed at IF (140 MHz). Modems employing QAM, but having a different number of modulation states are implemented to handle the required transmission capacity [2].

Transmitter

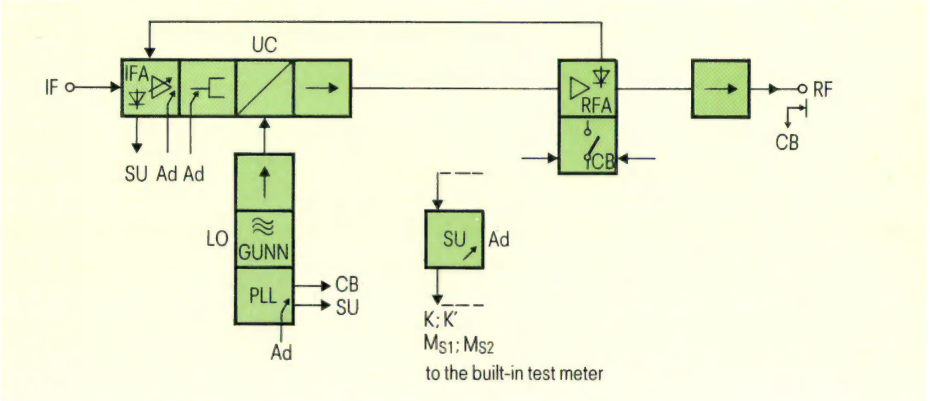
As shown in **Fig. 6** the transmitter is an assembly consisting of an up-converter, an integrated IF-amplifier, a local oscillator, an RF power amplifier and a supervision module.

The 140-MHz IF signal from the modulator is fed via the gain-controlled, linear IF amplifier to an up-converter. The local oscillator frequency for this mixer is generated by a PLL frequency stabilized Gunn-oscillator circuit with a low phase noise performance. The mixer operates as an SSB up-converter [5], converting the IF frequency to an RF frequency of either $f_{LO} + f_{IF}$ or $f_{LO} - f_{IF}$. The unwanted sideband and the local oscillator signal are typically suppressed by 20 dB with respect to the wanted sideband. This SSB mixer circuit, located in the *E* plane of a rectangular waveguide, is shown in **Fig. 7**. The mixer has been implemented in MIC technology using beamlead diode pairs manufactured by the Siemens Components Group.

The local oscillator consists of a voltage tunable RF oscillator and an integrated coupler with a harmonic mixing circuit and a PLL circuit to stabilize the RF frequency within $\pm 5 \times 10^{-6}$. The output signal of the up-converter is fed to an RF power amplifier which can be replaced by a traveling-wave tube amplifier (TWTA) with an output power of +33 dBm. In this particular application, the transmitter inset also incorporates an additional high-voltage power supply for the TWTA and the predistortion circuit, which is available as an option.

The solid state amplifier is implemented in MIC technology using GaAs FETs.

Its linearity is determined by selecting appropriate back-off with reference to the 1-dB compression point of the output power characteristic.



Ad	Adjustment	LO	Local oscillator
CB	Circuit breaker	M_{S1}; M_{S2}	Alarms
IF	Intermediate frequency	RF	Radio frequency
IFA	Transmit IF amplifier	RFA	RF power amplifier
K; K'	Alarm contacts	SU	Supervision unit
		UC	Up-converter

Fig. 6 Block diagram of the 18-GHz transmitter

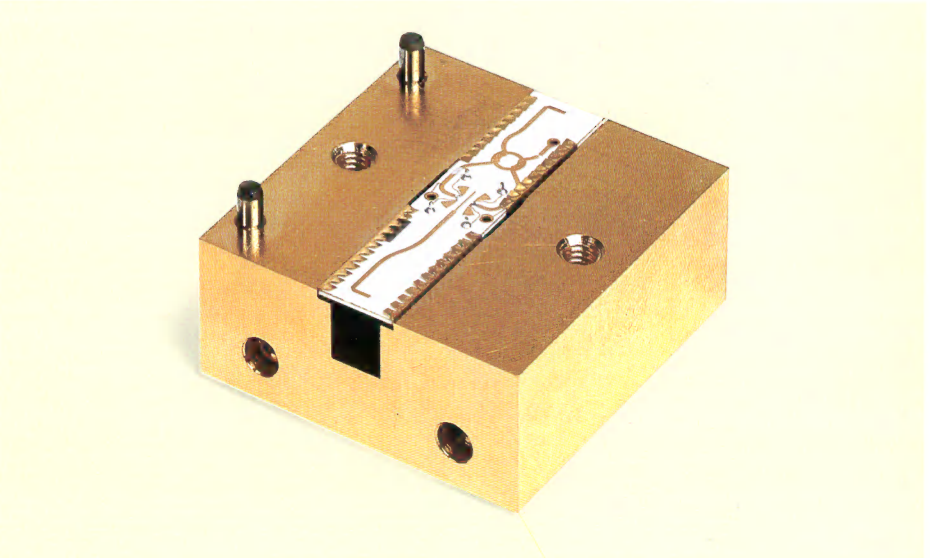
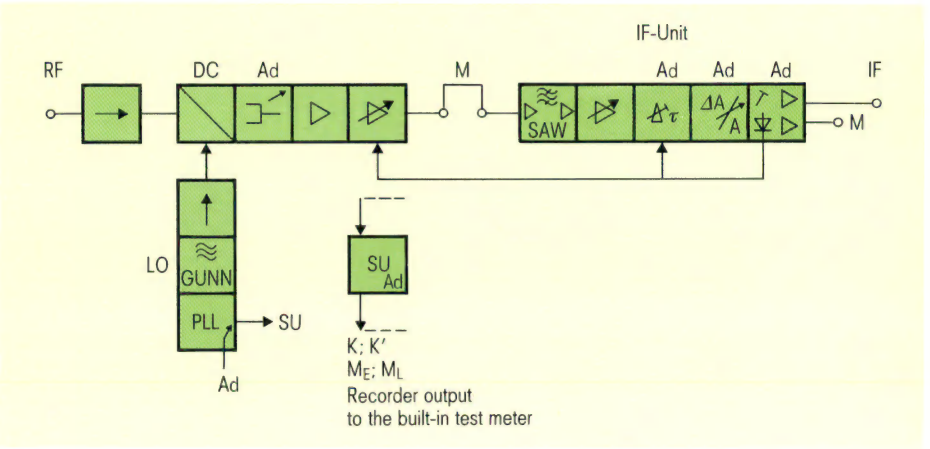


Fig. 7 18-GHz SSB converter, in MIC technology



ΔA/A	Adaptive IF amplitude equalizer	M	Test point
DC	Down-converter	M_E; M_L	Alarms
K1 K'	Alarm contacts	SAW	Surface acoustic wave roll-off filter
LO	Local oscillator	SU	Supervision unit
		Δ_τ	Three-stage delay equalizer with tilt equalizer

Fig. 8 Block diagram of 18-GHz receiver

The supervision module (**Fig. 6**) incorporates ac filters to suppress transient voltage swings, alarm signaling and supervision circuits and the diagnostic point for connecting a central in-service test meter.

Receiver

The block diagram of the receiver is shown in **Fig. 8**. The RF signal from the antenna is fed via the channel branching filter chain into the receiver. An isolator at the input ensures a good match to the channel filter. The down-converter MIC is of the SSB type. It converts the incoming RF signal to the IF range. The typical noise figure for this converter is less than 8 dB. To improve the system gain a low noise RF preamplifier can be used in front of the mixer. This RF preamplifier reduces the noise figure of the front end to ≤5 dB; the preamplifier has been realized as a single-stage MIC circuit using a very low noise GaAs FET.

The local oscillator for the receiver is similar to the oscillator circuit for the transmitter, the only difference being that the output power is about 5 dB lower.

The signal spectrum width at the intermediate frequency of the system is 140 MHz ± 35 MHz. The IF signal is amplified in a low-noise gain-controlled IF preamplifier. As indicated in **Fig. 8** the output signal of the IF preamplifier is fed to the main IF unit via a SAW filter. This SAW filter performs the Nyquist filtering on the receive side of the system. The roll-off factor may vary in the range from 0.2 to 0.5 depending on the system variant under consideration. The IF unit comprises an AGC main amplifier, a delay slope equalizer, a group delay equalizer and an adaptive amplitude equalizer. The group delay equalizer compensates for the group delay distortion caused by the RF channel filters. The SAW filter does not contribute to this distortion. The adaptive amplitude equalizer compensates for IF amplitude distortion caused by multipath propagation effects on the radio path between transmitter and receiver.

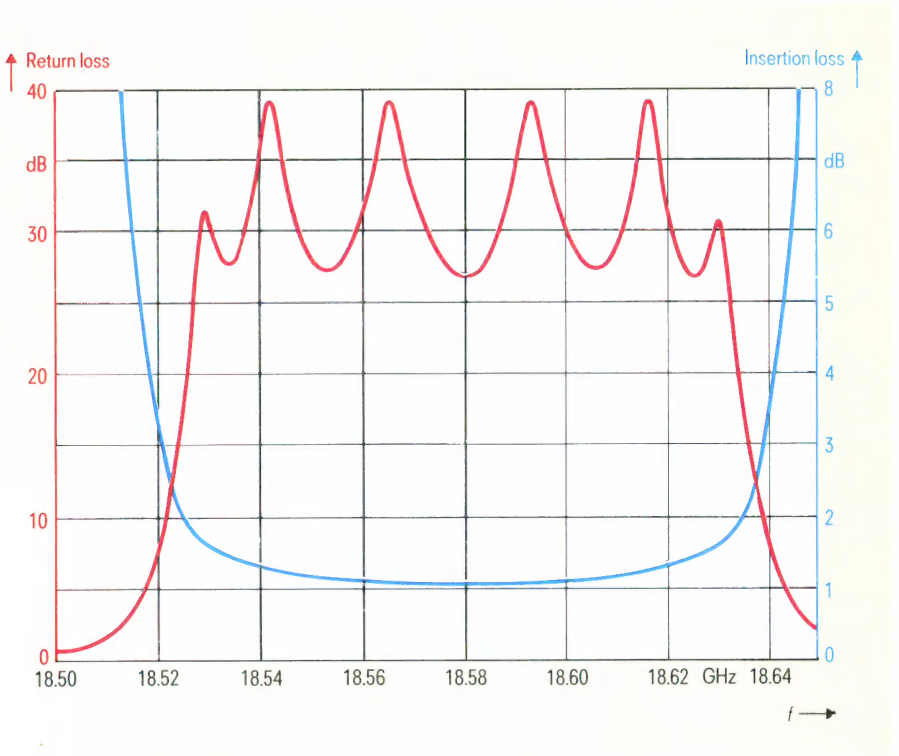


Fig. 9 **Insertion loss and return loss in passband for the channel branching filter**

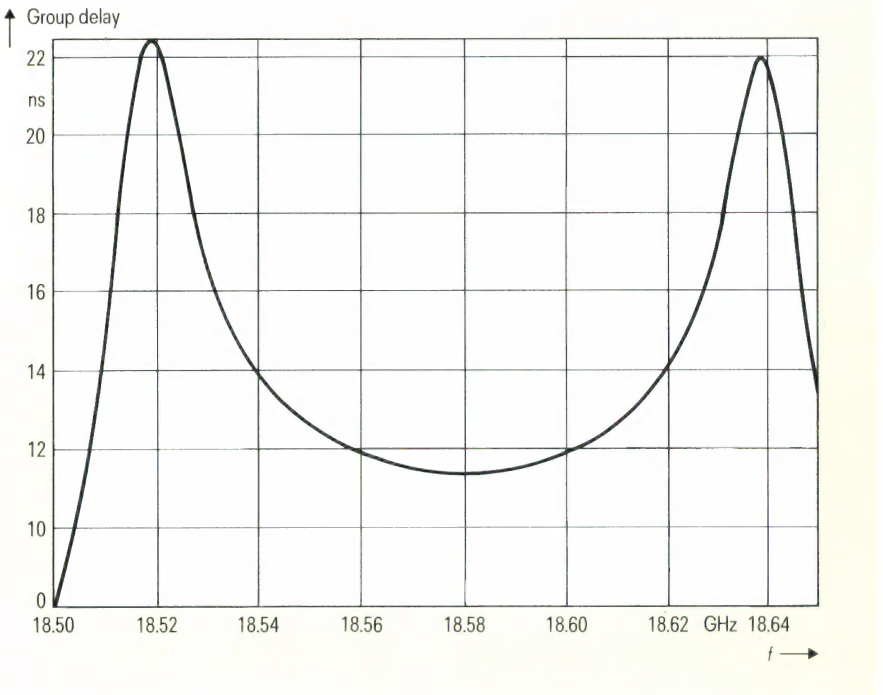


Fig. 10 **Group delay characteristic of the channel branching filter**

Channel branching filter

The channel branching filter consists of six waveguide resonators (sections) coupled to one another by apertures. Channel filters are available for 55-MHz, 80-MHz and 110-MHz channel spacing, as required by the chosen system variant. The filters all have the same mechanical length, so that it is easy to build up a channel branching filter chain in the RF connection unit. The connection between a channel filter and a transmitter or receiver is established by a flexible waveguide.

Figs. 9, **10** and **11** show the characteristics of a channel filter used for 110-MHz channel spacing (140 Mbit/s/4 QAM and 2 × 140 Mbit/s/16 QAM).

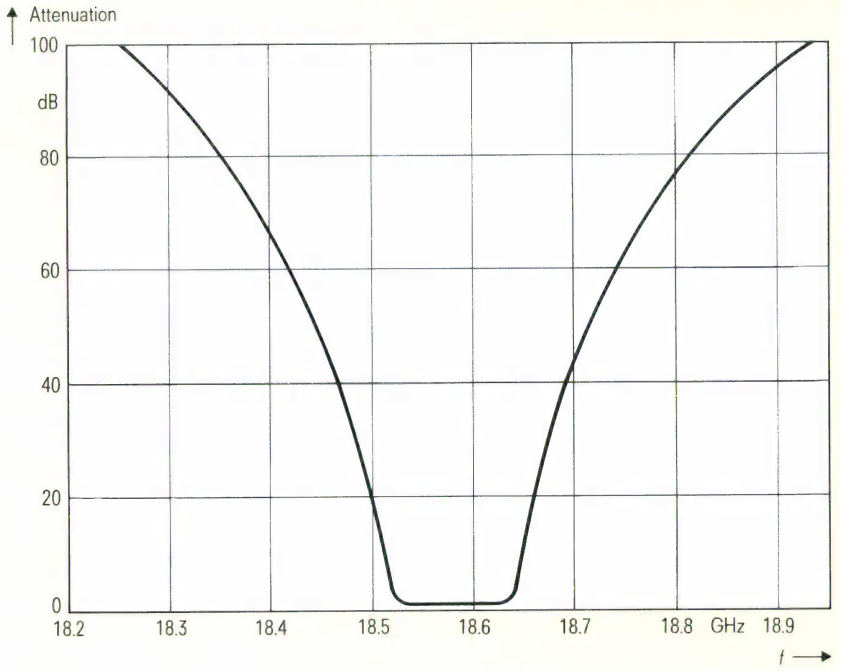


Fig. 11 Attenuation in passband and stopband for the channel branching filter

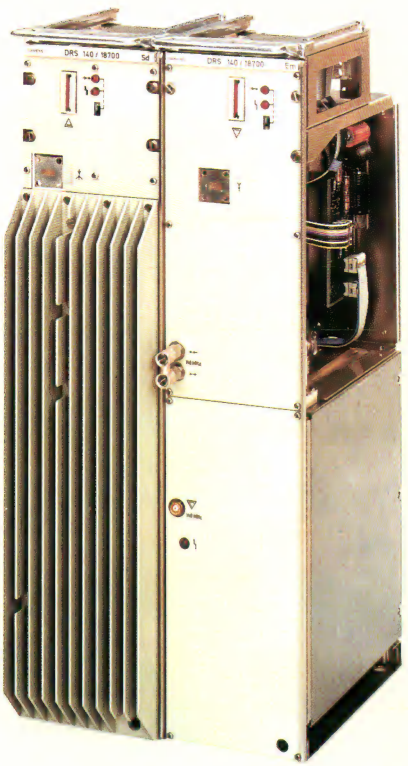


Fig. 12 RF insets for the 18-GHz band: transmitter (left) and receiver (right)

Power supply

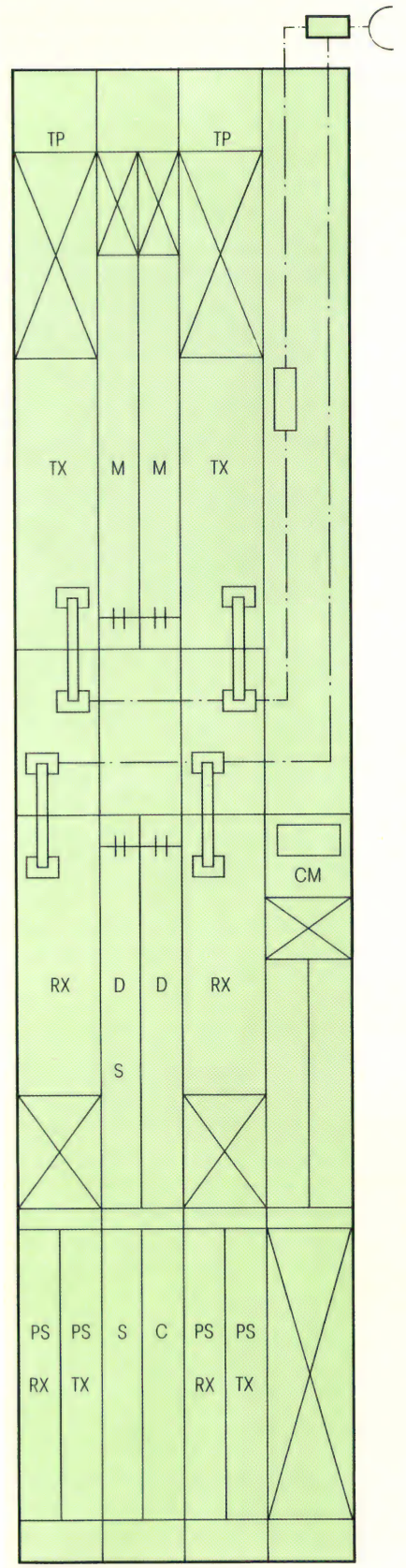
Separate identical power supply insets are used for the transmit and the receive sides. The power supply converts a dc battery voltage of 36 V to 75 V to the required dc voltage in the range of ± 5 V to ± 24 V for the operation of the components in the transmitter, the receiver and the modem. These power supplies are short-circuit-proof and have electrical isolation between the primary and the secondary side.

In-service test meter

As in all style 7R equipment, a centrally located in-service test meter (dc meter) is provided for monitoring and fault location purposes. It can be connected to the transmitter, receiver and modem via a multicontact connector. It is possible by means of this test meter, for example, to check the voltages of the power supply, the output power of the transmitter and the receive level. Only one test meter is required for several radio relay systems.

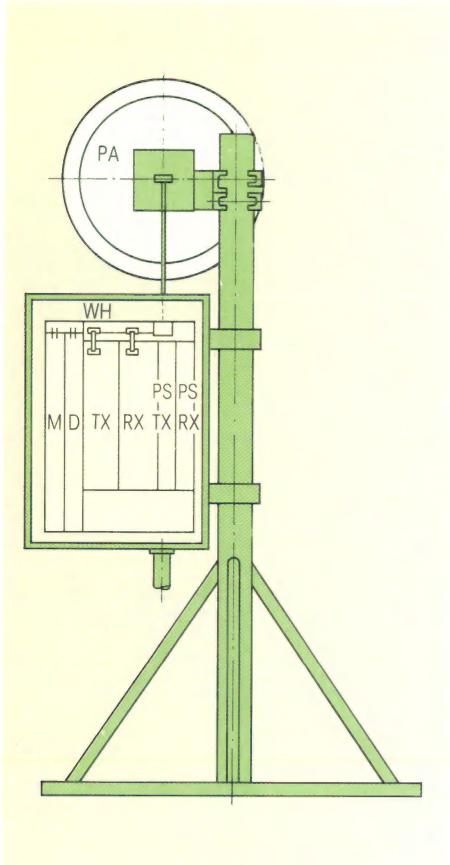
System supervision

The supervision modules are accommodated in the equipment insets on the transmit and receive sides. Any faults are generally indicated by LEDs on the



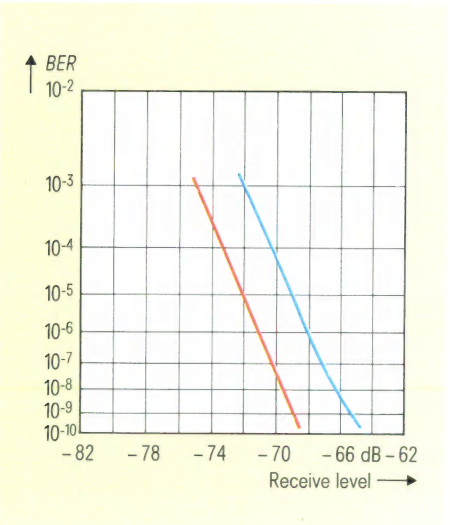
C	Control inset	RX	Receiver
CM	Test meter	S	Switching inset
D	Demodulator	TP	Terminal panel
M	Modulator	TX	Transmitter
PS	Power supply		

Fig. 13 Rack configuration for a 1 + 1 terminal



D	Demodulator
M	Modulator
PA	Parabolic antenna
PS RX	Power supply, receive side
PS TX	Power supply, transmit side
RX	Receiver
TX	Transmitter
WH	Weatherproof housing

Fig. 14 Outdoor terminal with weatherproof housing, parabolic antenna with 0.6 m diameter, and antenna mast



2 × 140 Mbit/s / 16 QAM / noise figure = 5 dB
1 × 140 Mbit/s / 4 QAM / noise figure = 9 dB
1 × 140 Mbit/s / 16 QAM / noise figure = 5 dB

Fig. 15 System characteristics (*BER* versus *RSL*)

faulty inset; alarm signals are also initiated. The alarm signals on the *transmit side* result from

- loss of baseband signal at the modulator input (MS1),
- loss of frame clock and data in the modulator (MS2),
- loss of IF signal at the modulator output (MS2),
- loss of synchronization in the local oscillator (MS2),
- loss of transmit output power (MS2),
- equipment faults, e.g. voltage failure (MS2).

On the *receive side* the alarms result from

- loss of channel identification or inadequate transmission quality (ML),
- loss of synchronization in the local oscillator (ME),
- loss of IF input level at the demodulator, loss of frame clock (ME),
- equipment fault (ME), e.g. voltage failure.

The alarm signals MS1, MS2, ML and ME are passed to a remote supervision facility via isolated contacts; they are also used as switching criteria for a protection switching equipment. Faults which result in the interruption of the wanted signal initiate an alarm signal and are indicated visually and audibly in the rack frame.

Mechanical design

All insets of the system, modem, power supplies, transmitter and receiver, are designed for installation in style 7R racks (indoor installation).

The transmitter and receiver occupy the full rack width of about 108 mm (**Fig. 12**), whereas the modem and power supply fill only half the rack width.

Fig. 13 shows the configuration of a terminal station for one operating channel and one standby channel.

The same type of insets as mounted in rack style 7R can be accommodated in a terminal station or repeater station in a weatherproof casing (**Fig. 14**). In addition to the equipment insets, this housing also contains the high voltage protection facilities. The casing and the parabolic antenna are normally mounted on a tubular mast with a 108-mm diameter. The antenna is connected to the RF combining circuit in the housing via a rectangular R 220 waveguide.

Electrical characteristics of the system family

Typical system data of the three main members in the system family are summarized in **Table 2**. The hypothetical fade margins, which are essential for link planning and can be derived from these data, are given for a 1-km hop with different antenna configurations.

In **Fig. 15** typical system characteristics showing the relation between the received signal level (*RSL*) and the bit error ratio (*BER*) are shown for the three main systems. In all three cases the degradation with respect to theoretical characteristics is very small down to very low bit error ratios.

The excellent spectrum shaping characteristics provided by the SAW filters and maintained by the linearity of the RF power amplifiers result in very small adjacent channel interference and make sure that the emitted spectrum lies well within the spectrum mask given by the FCC.

Examples for system planning

As already mentioned in the section on system planning, the performance objective for planning a high-capacity 18-GHz link is the permissible unavailability due to rain, expressed as a percentage of time. Based on this planning objective and rain intensity statistics, the appropriate system configuration is selected in which the transmit power level, the antenna diameter and the maximum feeder loss are specified, and the need for a low-noise preamplifier is established. **Fig. 16** shows a family of curves representing different antenna parameters which give the maximum feeder loss or feeder length for standard flexible waveguide (E 190) or overmoded bendable waveguide (SIRAL S70d). With an assumed unavailability of 0.005% per hop (less than 30 minutes per year), hop lengths of up to 10.5 km are possible, even in areas with heavy rain ($R_{0.01\%}$ = 63 mm/h).

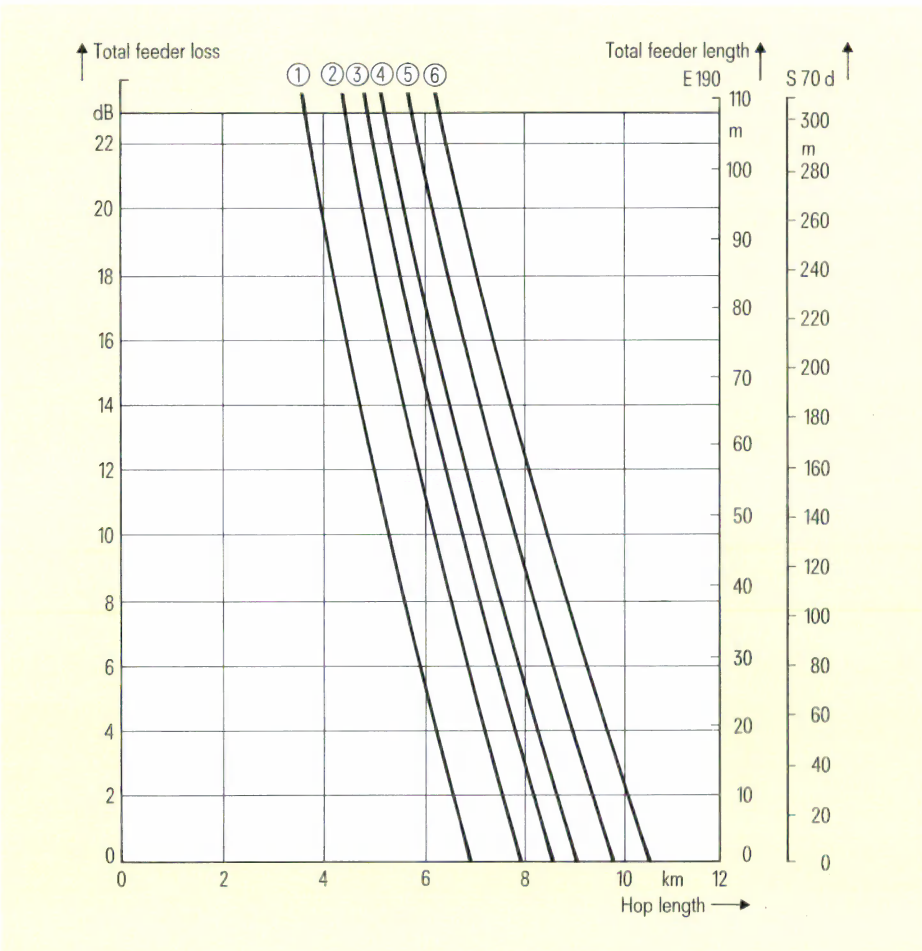
Conclusion

A new high-capacity radio relay system family for the 18-GHz band has been

System parameters		DRS 140/18700/4 QAM				DRS 140/18700/16 QAM				DRS 280/18700/16 QAM			
Symbol rate	MBaud	70				35				70			
Modulation format		4 QAM				16 QAM				16 QAM			
CEPT capacity } per carrier	Mbit/s	139.264				139.264				2×139.264			
FCC capacity } per carrier		3×DS3				3×DS3				6×DS3			
Transmit power level	dBm	20		33		17		33		17		33	
Preamplifier		No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Minimum receive signal level for $BER = 10^{-3}$	dBm	−75	−79	−75	−79	−71	−75	−71	−75	−68	−72	−68	−72
System gain	dB	95	90	108	112	88	92	104	108	85	89	101	105
1-km fade margin*													
for 2×0.6 m Ø antennas (G_A = 38.5 dB)	dB	49	53	62	66	42	46	58	62	39	43	55	59
for 2×1.2 m Ø antennas (G_A = 44.5 dB)	dB	61	65	74	78	54	58	70	74	51	55	67	71
for 2×1.8 m Ø antennas (G_A = 48.0 dB)	dB	68	72	81	85	61	65	77	81	58	62	74	78

* no feeder loss taken into account

Table 2 System parameters for digital radio relay systems operating in the 18-GHz band



Transmit power: P_t = 33 dBm
Receive power: P_r (10^{-3}) = −72 dBm
Antennas and antenna gain: 0.6 m; 38.5 dB, 65 dB; 1.2 m; 44.5 dB, 65 dB; 1.8 m; 48 dB, 70 dB
Branching filter loss: 5 dB
Zone H (rain intensity 63 mm/h in 0.001% per year), Outage = 0.005% per hop

Antenna configurations:
① 0.6 m + 0.6 m
② 0.6 m + 1.2 m
③ 0.6 m + 1.8 m
④ 1.2 m + 1.2 m
⑤ 1.2 m + 1.8 m
⑥ 1.8 m + 1.8 m

Fig. 16 Permissible feeder attenuation and length versus hop length (DRS 2 × 140/18700) for different antenna configurations

presented. Indirect modulation and advanced SAW filter technology enable up to 560 Mbit/s per RF to be transmitted and enable up to 4480-Mbit/s band capacities to be realized with maximum spectrum efficiencies of 6.8 bit/s/Hz. The strictly modular concept based on a building block approach and system versions suitable for indoor and outdoor installation provide for a flexible and economic adaptation to the special requirements of radio transmission in local and regional networks. The system family introduced here is an attractive transmission concept for route extensions and for frequency coordination in densely meshed networks.

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Helmut Junghans and Klaus Otremba

Up- and Down-Converters for Wideband Digital Radio Relay Systems

Converter circuits for wideband digital radio relay systems, unlike those for frequency-modulated analog radio relay systems, have to satisfy exacting amplitude and phase linearity requirements on account of the multilevel modulation techniques employed. Moreover, as the number of levels increases, these modulation techniques require increasingly higher signal-to-noise ratios, necessitating correspondingly lower receive noise figures.

In the following article the authors refer to the DRS 140/6700 radio relay system in describing a new circuit configuration employed in the design of the up- and down-converters and report the electrical values obtained. The results presented are not, however, specific to a particular application but are applicable to digital wideband radio relay systems in general.

The DRS 140/... series of radio systems for 3.9 GHz, 6.7 GHz and 11.2 GHz employs 16 QAM (16-level quadrature amplitude modulation) as its modulation method and operates at an intermediate frequency (IF) of 140 MHz [1, 2]. The modulated IF signal is produced by the modulator of the DRM 140/140 modem equipment which is separate from the radio equipment [3, 4]. Spectrum shaping is provided at IF with the aid of surface acoustic wave (SAW) filters in the modem, thus eliminating this function from the radio equipment.

The function of the converter modules is to transpose the modulated IF signal from the 140-MHz band to the relevant radio-frequency (RF) band on the transmit side and to translate it back from the RF band to the IF on the receive side. For this purpose, it is usual to employ converter circuits, operating on the additive mixing principle. The converters for the DRS 140/... series of systems

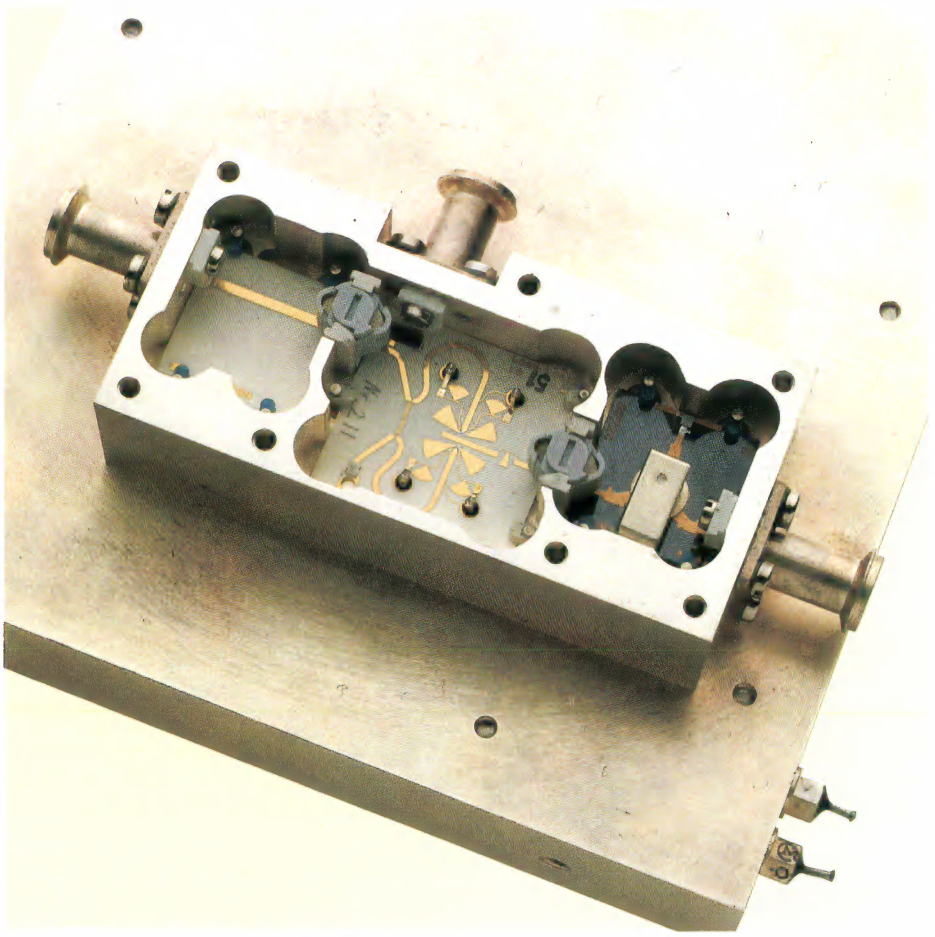

Fig. 1 The 140/6700-MHz up-converter with gain-controlled intermediate-frequency (IF) driver amplifier, a mixer drive circuit and the circuit of the microwave converter on a ceramic substrate

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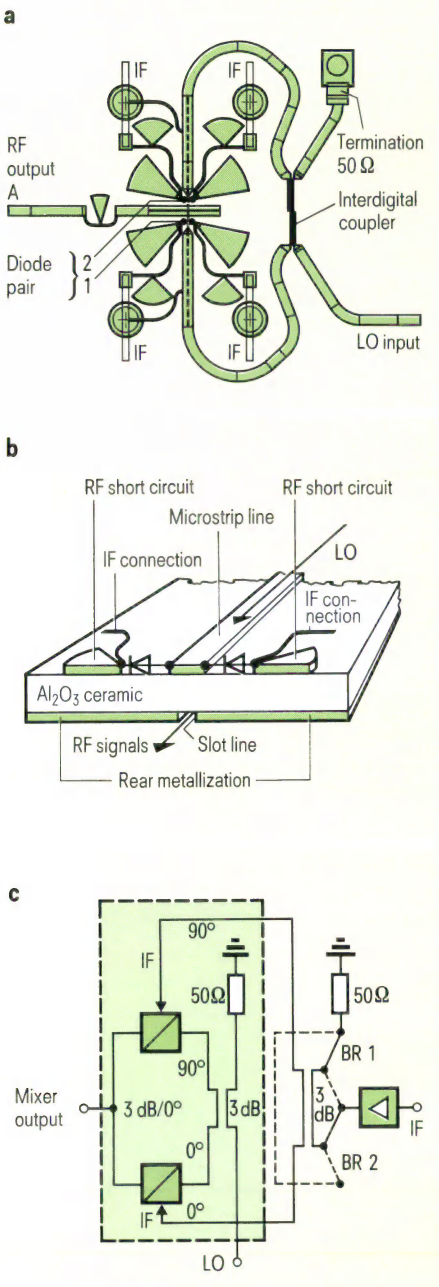


BR Strap
IF Intermediate frequency
LO Local oscillator
RF Radio frequency

Fig. 2 Circuit configuration of the 140/6700-MHz up-converter
a Circuit layout
b Location of the slot line
c Functional diagram

are designed as integrated circuits in thin-film technology with a new circuit configuration. Specially developed double beam-lead diodes were employed for this purpose. They surpass all requirements for amplitude and phase linearity as well as the receive noise figure by a clear margin. These converter modules for the DRS 140/... series of systems are described in the following paragraphs by reference to the circuits for the 6.7-GHz system.

The 140/6700-MHz up-converter

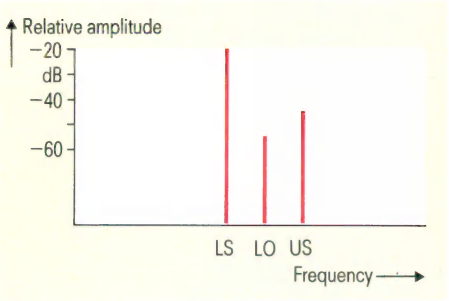
Mechanical design

The up-converter incorporates a gain-controlled IF driver amplifier, a mixer drive circuit and the circuit of the microwave converter on a ceramic substrate (**Fig. 1**). The up-converter was designed as what is known as a single-sideband suppressed carrier converter. This simplifies the overall design and operation of the transmitter inset considerably because it makes the otherwise essential sideband filter superfluous. Basically, the up-converter produces at its output port only one modulated sideband.

Electrical design and mode of operation

The mode of operation of the single-sideband up-converting mixer is clearly demonstrated by the circuit configuration shown in **Fig. 2**. Further information on the operating principle may obtained from the illustration in [5]. The up-converter is an integrated circuit in NiCr-Cu-Au thin-film technology on an Al_2O_3 ceramic substrate (1 inch × 1 inch).

The main electrical functions of the converter can be seen in **Fig. 2a** in the plan view of the new circuit layout employed in this configuration. In the lower section of **Fig. 2a** is an interdigital coupler. This divides the pump power from the transmitter oscillator into two signals which are of equal power but displaced in phase by 90° and fed to the four Schottky diodes of the converter. These four mixer diodes, in the form of double beam-lead pairs, lie between the points of the centrally located circular segments and the feed lines referred to as coming from the RF coupler. The circular segments are dimensioned to provide a virtual short circuit at 6.7 GHz at the points of contact with the diodes. Since this is not a dc short, it is possible for both the 140-MHz IF signal from the drive circuit and a dc bias voltage to be fed to the diodes via these wedge-shaped stubs and the high-impedance microstrip transmission lines. Silver ribbons soldered to four pins connect the converter to the mixer drive circuit. The pins



LO Local oscillator
LS Lower sideband
US Upper sideband

Fig. 3 Typical output spectrum of the 140/6700-MHz up-converter for a constant oscillator frequency

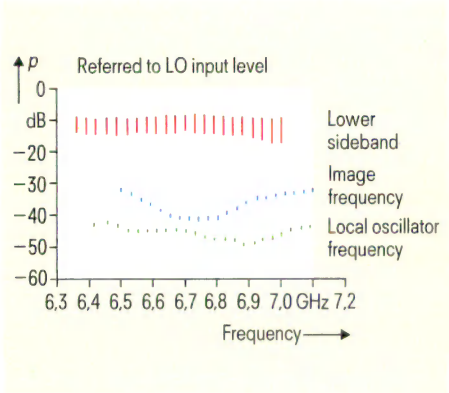


Fig. 4 Output spectrum of the 140/6700-MHz up-converter swept across the frequency band

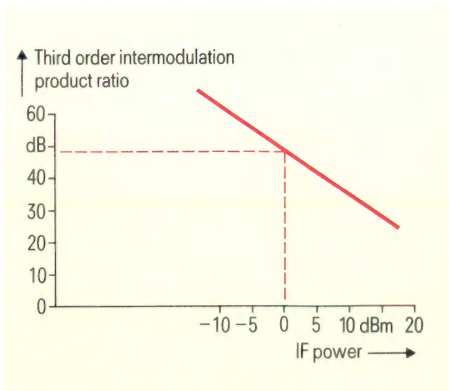


Fig. 5 Third order intermodulation product of the mixer as a function of the intermediate-frequency (IF) input power

project through the drilled ceramic substrate and through the IF board mounted on the rear of the module. Each diode pair in conjunction with a slot line on the back of the ceramic substrate forms a balanced mixer. The slot line is located symmetrically beneath the two transmission lines leading to the 3-dB coupler (**Fig. 2b**). In the mixer drive circuit, the

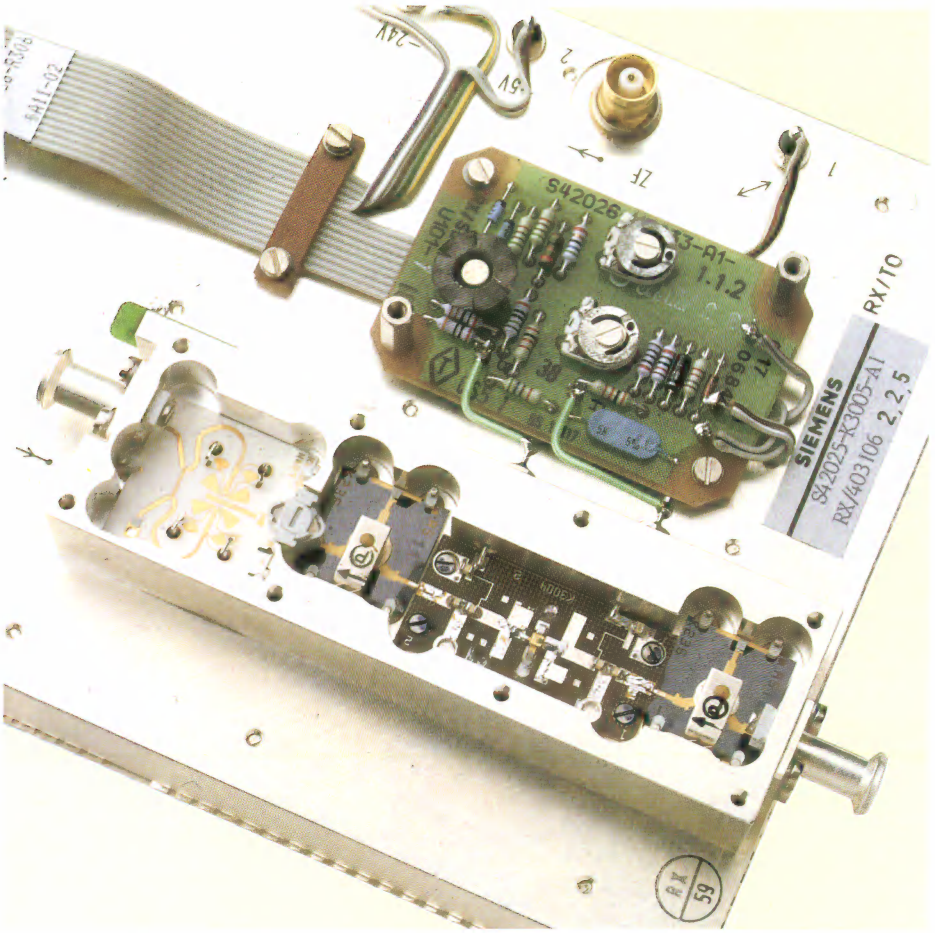


Fig. 6 The 6700/140-MHz down-converter with center section opened and with the flange connector for the RF signal input on the right and the flange connector for the local oscillator signal on the left

IF signal from the IF driver amplifier is divided into two identical signals displaced in phase by 90°. Each IF signal from the drive circuit is fed to one diode pair of the up-converting mixer.

The interconnection of two balanced mixers and two 3-dB/90° couplers thus produces a bridge circuit (**Fig. 2c**) which acts like a single-sideband mixer. The typical output spectrum for a constant oscillator frequency is shown in **Fig. 3**. In this case, the lower sideband (LS) is the preferred output from the mixer. The upper sideband (US) is made the preferred output by relocating the two straps in the mixer drive circuit (BR1 and BR2 in **Fig. 2c**).

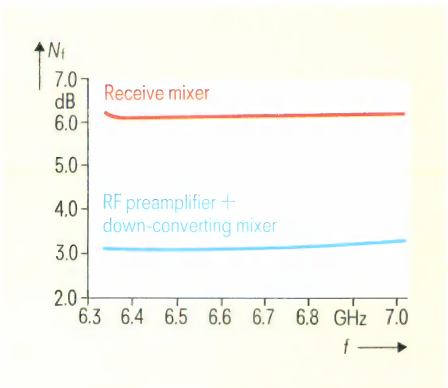


Fig. 7 Noise figure N_f of the down-converting mixer and of the overall module

Test results

As can be seen in **Fig. 2a**, the compact configuration of the individual balanced mixers and of the overall mixer circuit made it possible to keep short those lines which are important for the wideband operation of the bridge circuit.

Fig. 4 shows the frequency response of the lower sideband, which was selected in this case, as well as the residual image and local oscillator frequencies at the output port of the converter as measured with a spectrum analyzer.
The image frequency is typically better than 23 dB down relative to the selected sideband, while the local oscillator isolation referred to the LO input level is typically better than 40 dB.

The third order intermodulation products were determined using the two-tone method.

Fig. 5 shows the third order intermodulation product as a function of the IF input power. The operating point of the converter was selected so that, when the up-converter is inserted in the system, the residual nonlinearity of the mixer is small relative to the contribution by the output amplifier.

The 6700/140-MHz down-converter

Mechanical design

The down-converter comprises a low-noise, single-stage field-effect transistor (FET) preamplifier and an IF amplifier circuit with matching circuit for the mixer. **Fig. 6** shows the microwave section of the module opened. The flange connector for the RF signal input can be seen on the right, with the connector for the local oscillator signal at the other end. Isolators are located between the RF signal input and the input of the RF preamplifier as well as between the output of the RF preamplifier and the mixer input. The IF preamplifier is mounted on the other side of the package below the microwave section. Since the down-converter, like the up-converter, is designed as a single-sideband mixer, it does not require a band-pass filter between RF preamplifier and mixer. The sideband required to be received is selected by plug-in straps in the IF section of the matching circuit.

Electrical design and mode of operation of the down-converter

The design and mode of operation are similar to those of the previously described up-converter. The RF signal for down-conversion is fed into the converter at A (**Fig. 2a**). The horizontal microstrip line couples to a slot line which is located on the bottom of the substrate and runs vertical to this microstrip line. The signal energy is divided by the slot line between two balanced mixers which receive the local oscillator energy via an interdigital coupler and a microstrip line. The IF signal derived by mixing is fed via RF transmission line filters connected at four points (IF) of the circuit to the matching circuit located in the IF section. One of these

four RF filters consists basically of two wedge-shaped stubs (**Fig. 2a**) which are interconnected via a high-impedance line. The matching circuit is of similar design to that of the up-converter.

Test results

While the noise figure of the mixer including IF preamplifier is less than 6.5 dB (**Fig. 7**), the overall module with low-noise RF preamplifier has a noise figure of typically 4 dB. The image frequency rejection and the local oscillator isolation for the mixer alone have similar values to those of the up-converter. The operating points for the RF preamplifier and the dynamic range of the down-converting mixer and of the IF preamplifier are selected so that the slight nonlinearity of the overall module has no effect on system quality.

Summary

This article has described mixer circuits developed for use in the equipment of the DRS 140/... series of systems employing 16 QAM. In the future, systems employing 64 or 256 QAM will become increasingly important. The even higher number of levels employed in these modulation techniques will raise the linearity requirements for all the transmission circuits in the signal path quite considerably. However, even these more stringent requirements can be met by the new circuit configurations employed in the converters presented here, as experimental tests have already confirmed.

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Linear RF Power Amplifiers for High-Capacity Digital Radio Relay Systems

The performance of state-of-the-art microwave power amplifiers for use in high-capacity digital radio relay systems is reviewed. After the description of a typical GaAs FET power amplifier used in a 140-Mbit/s radio relay system with 16 QAM, emphasis is put on characterization techniques for amplifier nonlinearities, including measured degradation of system characteristics.

As an example of the state of present technology, the performances of a high-linearity traveling-wave tube amplifier (TWTA) and a 10-W GaAs FET solid-state power amplifier (SSPA) are compared for 16-QAM and 64-QAM signals. The applicability of predistortion techniques to GaAs FET amplifiers is demonstrated. Finally, the potential of high-voltage GaAs FETs is investigated as a new and promising way to substantially improve amplifier linearity.

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Introduction

In the present generation of high-capacity digital radio relay systems there are two types of RF power amplifiers: traveling-wave tube amplifiers (TWTAs) and solid-state power amplifiers (SSPAs) using GaAs FETs. In the lower frequency bands (<7 GHz) and for a moderate number of modulation levels (e.g. 16 QAM) the SSPA dominates, whereas at higher frequencies (>11 GHz) and for higher linearity requirements (in 64-QAM applications) the TWTA has a clear performance advantage.

Evolution in the field of GaAs semiconductor technology will gradually allow fulfillment of the demand for SSPAs in future radio relay systems which mainly comes from the system operators. However, this tendency is slowed down by the accompanying development of radio system technology to more spectrally efficient modulation formats. For equal or increased transmission capacity per carrier, a higher available output power and better linearity is in principle unavoidable, so that straightforward (or brute-force) techniques soon find their limitations.

To push SSPAs beyond their present limits requires refinements in many fields, beginning with improvements in device and circuit design and including sophisticated techniques, such as adaptive compensation and linearization. Even system layout and design will contribute to this development. To cope with propagation induced distortion in radio relay systems using multilevel modulation, space-diversity reception is nearly universally employed. This reduces the maximum fade depth so that smaller sys-

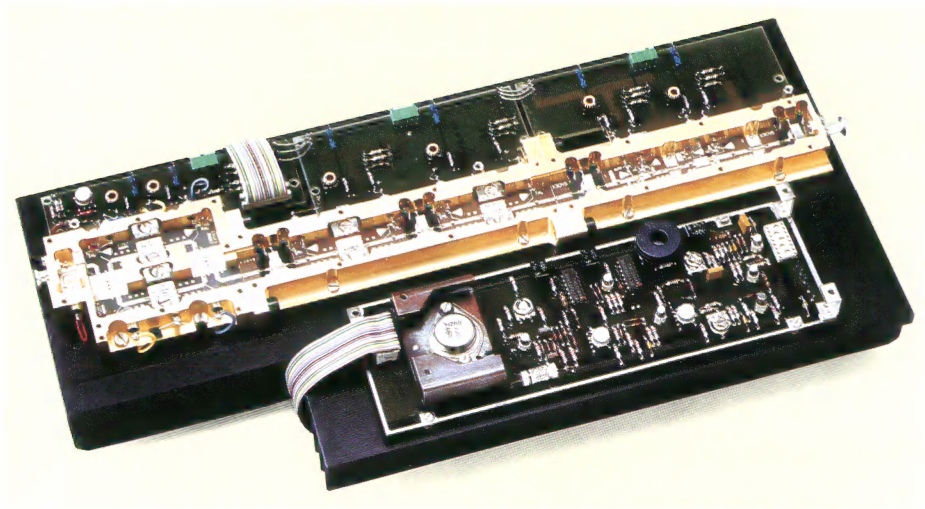

Fig. 1 Multistage GaAs FET power amplifier providing 1 W in the frequency band of 6.4 to 7.1 GHz

Frequency (GHz)	Modulation format	Free-space loss (dB)	Antenna gain (dB)	Receiver threshold $BER = 10^{-3}$ (dBm)	System margin (dB)	Transmitter output power (dBm)
6.7	16 QAM	142.9	87	–74	30 35 40	22 27 32
6.2	64 QAM	142.2	85.6	–68	30 35 40	28 33 38

Assumptions: Hop length: 50 km,
Antenna diameter: 3 m,
Branching and feeder loss: 10 dB

Table 1 Typical requirements for 140-Mbit/s systems

tem margins can be tolerated and output power requirements reduced. This paper presents an overview of present-day GaAs power FET amplifier technology. After a review of basic system requirements and the nonlinearity behavior of GaAs power FETs, a short description is given of a 1-W amplifier for a 16-QAM radio relay system currently in production. Then emphasis is put on characterization techniques for moderately nonlinear devices by practical methods and their relation to system behavior for 16- and 64-QAM applications. The potential of high-voltage GaAs FETs as a new and special way to improve amplifier performance is explored.

Basic system requirements

The two main requirements for the power amplifier in a high-capacity digital radio relay system are output power and linearity. The demand for output power is dictated by the necessity for an adequate system fade margin as given by the signal-to-noise ratio requirement at the receiver-demodulator input, and depends mainly on the modulation format employed. Based on fade statistics of an average hop, typical fade margins are on the order of 35 to 45 dB. Straightforward calculations based on system and technology parameters then lead to output power levels on the order of 1 to 10 W.

Linearity specifications are more difficult to deduce. The most suitable, but also most tedious, characterization is based on degradation of *BER* versus received signal level (RSL) characteristics [1]. Other characterizations are based on two- or three-tone intermodulation ratios [2, 3], leading to the definition of an intercept point (ICP) or an intermodulation factor, e.g. M 3. However, most of these definitions, which are considered suitable for well-behaved ("third-order") nonlinearities such as those of TWTAs, are less valuable for GaAs FET amplifiers because of their more complicated behavior.

In practice, nonlinearity for QAM signals is sometimes described by the intermodulation sidebands added to the main spectrum of such a signal, defining a sidelobe-mainlobe ratio [1]. Typical system requirements for 140-Mbit/s systems with 16 and 64 QAM are summarized in **Table 1.**

Basic nonlinearities of GaAs FETs

The behavior of modern high-linearity TWTAs is dominated by one main nonlinearity caused by the interaction of the delay structure and the electron beam at excitation levels, resulting mainly in AM/PM conversion [4]. The situation for GaAs FETs, and especially for multistage GaAs FET amplifiers, is more complex.

In GaAs FETs at least three sources of nonlinearity usually must be considered in the moderately nonlinear region: the nonlinear gate-source capacitance, the transconductance nonlinearity and the nonlinear output impedance. These individual contributions depend on physical GaAs FET parameters and the embedding circuits on the input and output sides. The overall nonlinear characteristics can be quite complicated. At very high signal levels, the behavior of GaAs FETs is finally dominated by current and voltage limits (clipping), resulting from the static device characteristics and from drain-gate avalanche breakdown [5].

As a practical approach to describing GaAs FET nonlinearities in circuits, load pull techniques are commonly used, relating gain and intermodulation ratios to the load impedance [6]. It is generally found that the available gain and intermodulation behavior are interrelated. The design of single-stage amplifiers for linearity must be based on such load pull results and include a search for "optimum" embedding circuits giving the best intermodulation performance.

Example of a GaAs FET amplifier in production

As an example of such a multistage realization, a GaAs FET power amplifier providing 1 W for a 140-Mbit/s

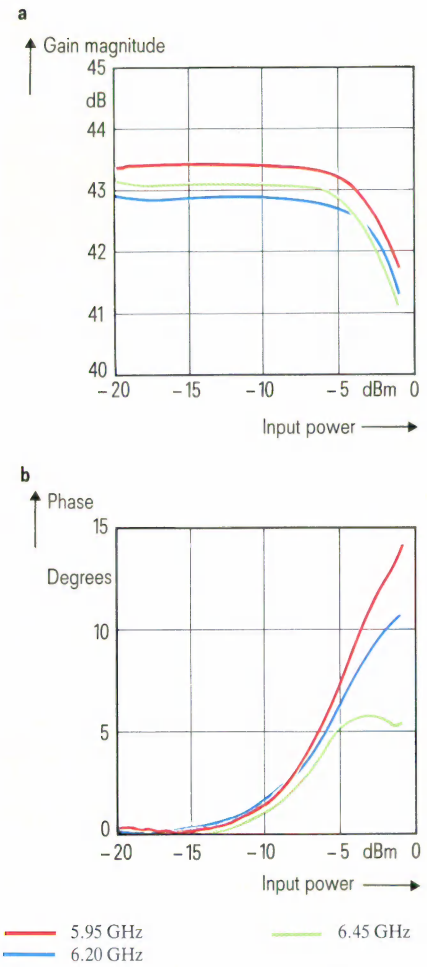

Fig. 2 Large signal gain magnitude (a) and large signal phase (b) versus input power of GaAs FET SSPA

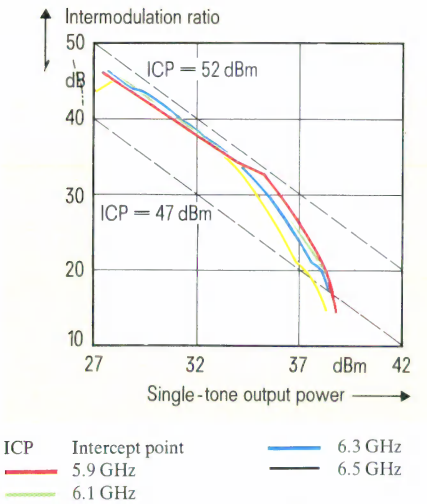

Fig. 3 Third-order intermodulation ratio versus single-tone output power (GaAs FET SSPA)

16-QAM radio system (DRS 140/6700) operating in the upper 6-GHz band is shown in **Fig. 1.** This five-stage amplifier provides a maximum linear gain of 39 dB, flat to within 1 dB over the 6.4- to 7.1-GHz band. The output stage uses two 3-W GaAs FET devices connected in parallel by 3-dB hybrids. To facilitate circuit design and production, the amplifier consists of three blocks each containing two transistors; the individual blocks are interconnected by microstrip isolators on ferrite substrates. With the exception of the 3-dB hybrids, which are realized as Lange couplers on alumina substrates, softboard technology with glass-fiber reinforced Teflon substrates is employed in the RF section of the amplifier. The circuit boards adjacent to the milled and gold-plated housing of the RF section contain the bias regulating and control circuitry. The whole amplifier is mounted on a heat sink providing the necessary heat dissipation capability.

Multistage amplifiers are usually designed in such a way that mainly the driver and output stages, which consume most of the dc power, contribute to intermodulation [7]. To date, no satisfactory techniques for internal compensation of the contributions from different stages are known.

Experimental characterization of multistage GaAs FET amplifiers

According to the basic principles mentioned above, a linear multistage amplifier was recently developed for the 6.2-GHz band capable of about 10-W output power at the 1-dB compression point. The large-signal transfer characteristics were measured with a computer-controlled vector network analyzer.

Results for this amplifier, which can be considered representative for the state-of-the-art, are shown in **Figs. 2** and **3**. Small-signal gain varies by about 1 dB over the frequency band, the 1-dB compressed output power level is 40.3 dBm at midband (**Fig. 2a**). Transmission phase versus power level characteristics show a marked change with frequency (**Fig. 2b**). However, both curves, gain magnitude and phase, show only small and smooth variations with power level. Both characteristics are obtained by quasi-static measurements and may be marked by thermal effects.

As dynamic nonlinearity tests, two-tone intermodulation measurements have been performed. **Fig. 3** shows the results

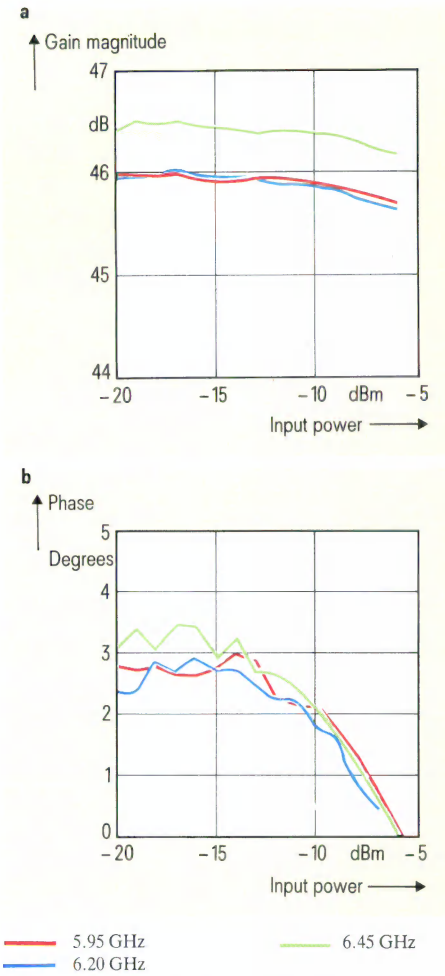

Fig. 4 Large signal gain magnitude (a) and large signal phase (b) versus input power of TWTA

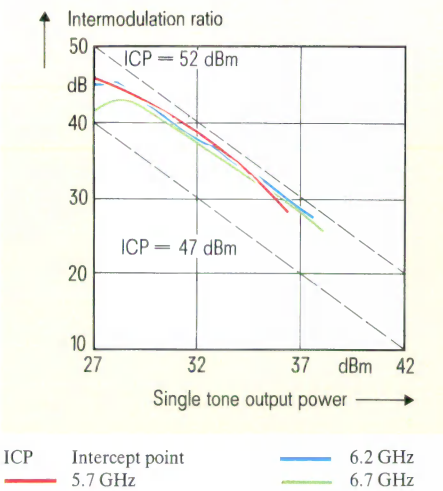

Fig. 5 Third-order intermodulation ratio versus single-tone output power (TWTA)

for four different frequencies. Third-order intermodulation ratios are given versus single-tone power levels. At low power levels, the behavior is nearly third-order with significant deviations around the 1-dB compression point.

Amplifier type	Power consumption (W)	1-dB compression point (dBm)	Intercept point (dBm)	Single-tone output power for IM3			
				30 dB (dBm)	35 dB (dBm)	40 dB (dBm)	45 dB (dBm)
RW 289 (TWT)	103	–	51.5	36.5	34.0	31.4	28.8
GaAs FET	78	40.3	51.2	35.3	33.3	30.8	28.3

Table 2 Comparison of amplifiers (6.2 GHz)

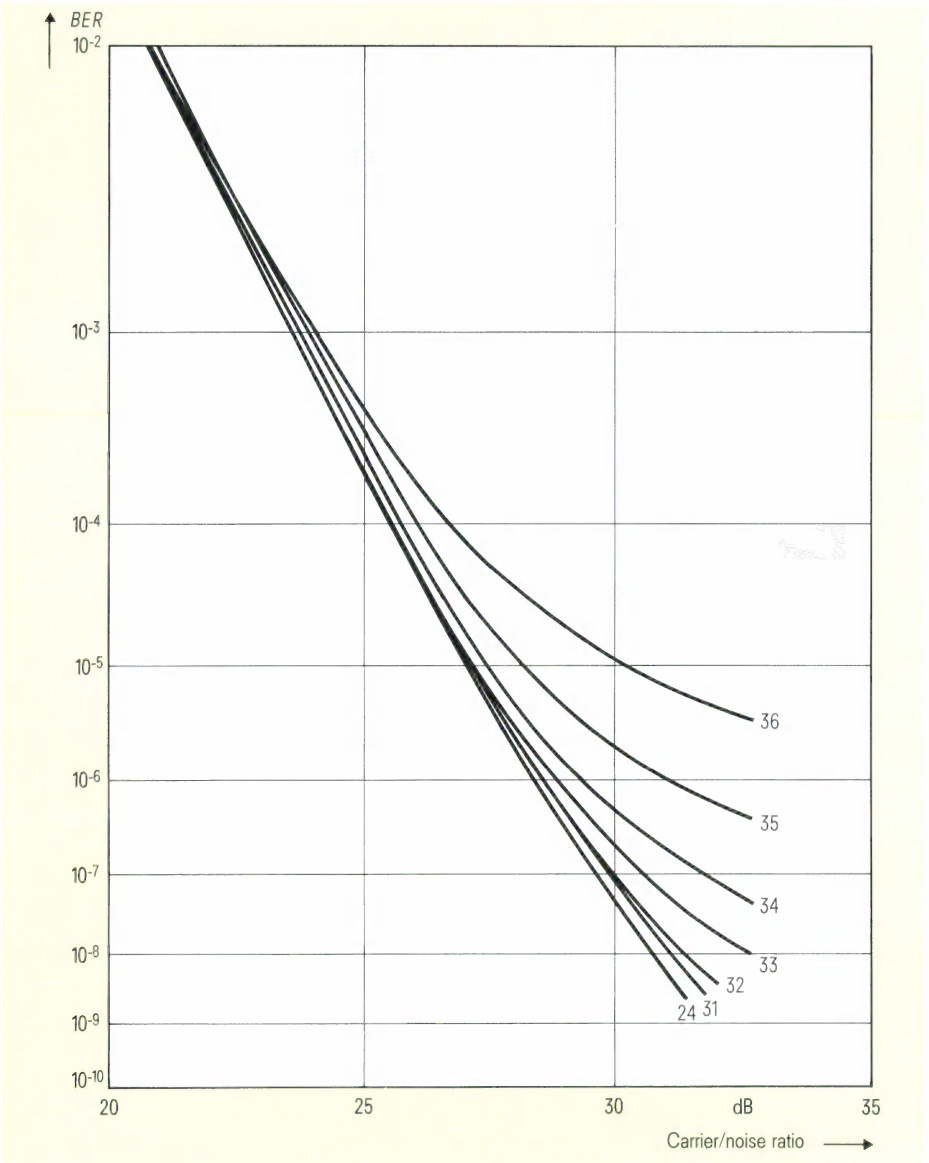

Fig. 6 ***BER*** **versus** ***C/N*** **characteristics of 64-QAM system with GaAs FET SSPA (parameter: output power in dBm)**

This behavior is typical for a cascade of a small third-order nonlinearity and a limiting device.

TWTA characterization

Similar characteristics of a modern high-linearity TWTA (RW 289, Siemens AG) are shown in **Figs. 4** and **5**. The dependencies of gain magnitude and phase on the power level are considerably smaller and smoother than for the GaAs FET amplifier. The transmission phase decreases with increasing power level (**Fig. 4b**), in contrast to the behavior of most GaAs FET amplifiers. The intermodulation ratio shows a nearly ideal third-order behavior over a wide power range, giving an almost constant intercept point (**Fig. 5**). Its value of 51 dB is of the same order as for the GaAs FET amplifier. Relevant data for comparison, including power consumption, are compiled in **Table 2**.

Amplifier characterization in QAM systems

The effects of amplifier nonlinearity were finally tested in multilevel QAM radio systems, using 16 and 64 QAM with a symbol rate of approximately 35 MBaud. For ease of measurement, a commercial noise and interference test set was used which adds noise at the IF level between receiver and demodulator. This results in the classical *BER* versus *C/N* characteristics. Data for the described GaAs FET amplifier are shown in **Fig. 6**.

Fig. 7 is a different representation of these data; the *BER* is plotted versus amplifier output power level with the *C/N* as a parameter. Both representations demonstrate that an output power of up to 31 dBm is possible with negligible degradation (less than 0.2 dB at *BER* of 10^{-8}). This means an output power backoff from the 1-dB compression power of about 9 dB. **Fig. 7** emphasizes that it is essential to characterize amplifier induced degradations at low *BER*s.

Comparison of 16 QAM and 64 QAM

Fig. 8 shows *C/N* degradation versus output power level, both for 16-QAM and 64-QAM systems.

The 16-QAM modem is a standard 140-Mbit/s unit equipped with a 7-tap transversal equalizer, giving nearly ideal theoretical performance [8]. The 64-QAM modem is a laboratory prototype. The same RF units were used in all these measurements.

Fig. 8 presents the measured degradation of the *BER* characteristics ($\Delta C/N$) versus output power level at *BER*s of 10^{-4}, 10^{-6} and 10^{-8}. At a *BER* of 10^{-8}, the difference in available output power for 16 and 64 QAM only slightly depends on permitted degradation; the $\Delta C/N$ values are between 2.1 and 2.3 dB. Extrapolating these data to very low degradations results in a limit of

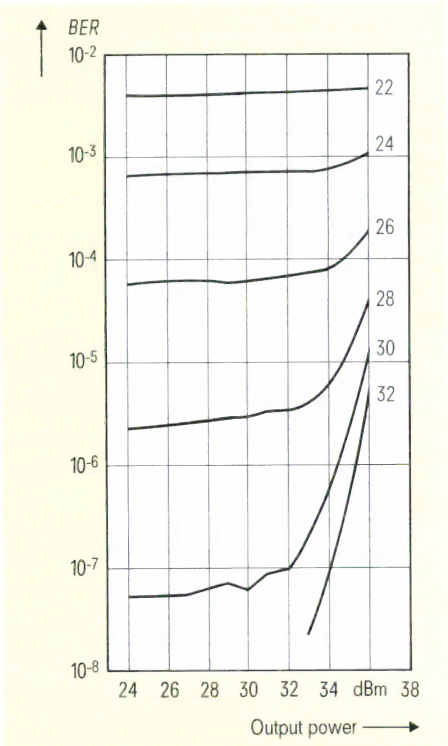

Fig. 7 ***BER*** **versus output power of GaAs FET SSPA for 64-QAM system (parameter:** ***C/N*** **in dBm)**

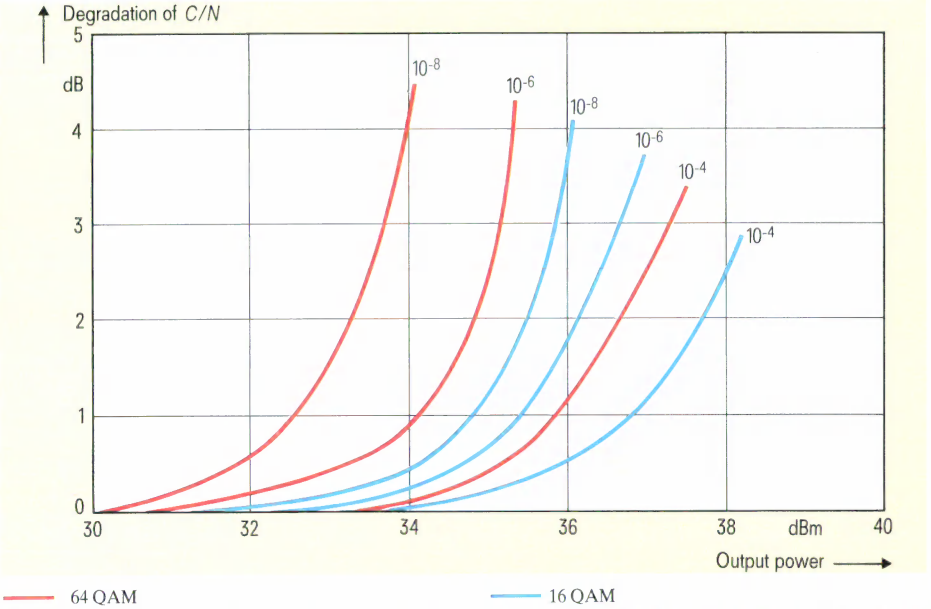

Fig. 8 Degradation of ***C/N*** **(**Δ ***C/N***) **versus output power for GaAs FET SSPA with 16 QAM and 64 QAM (parameter:** ***BER***)

approximately 3 dB for the difference in power capability between 16- and 64-QAM systems.

Linearity improvement techniques

Different methods have been proposed to improve the power capability or linearity of power amplifiers at a given dc input. Indirect methods of avoiding the consequences of nonlinearities, such as forward error correction (FEC), are not considered here. Predistortion is a well-proven technique to compensate the amplifier nonlinearity by a predistorter with a matched inverse nonlinearity.

The 64-QAM system characteristics given in **Fig. 9** for an output power level of 33 dBm show that a relatively simple IF predistorter preceding the up-converter (originally developed to linearize a TWTA) can reduce nonlinearity effects considerably. Alignment of such a predistorter is a complex task. A constellation display is very helpful for coarse tuning. Fine adjustment for minimum intermodulation sidelobes of a QAM spectrum has not proved effective for 64 QAM; direct *BER* monitoring turned out to be most successful. Such strategies will be significanct for future adaptive predistortion techniques.

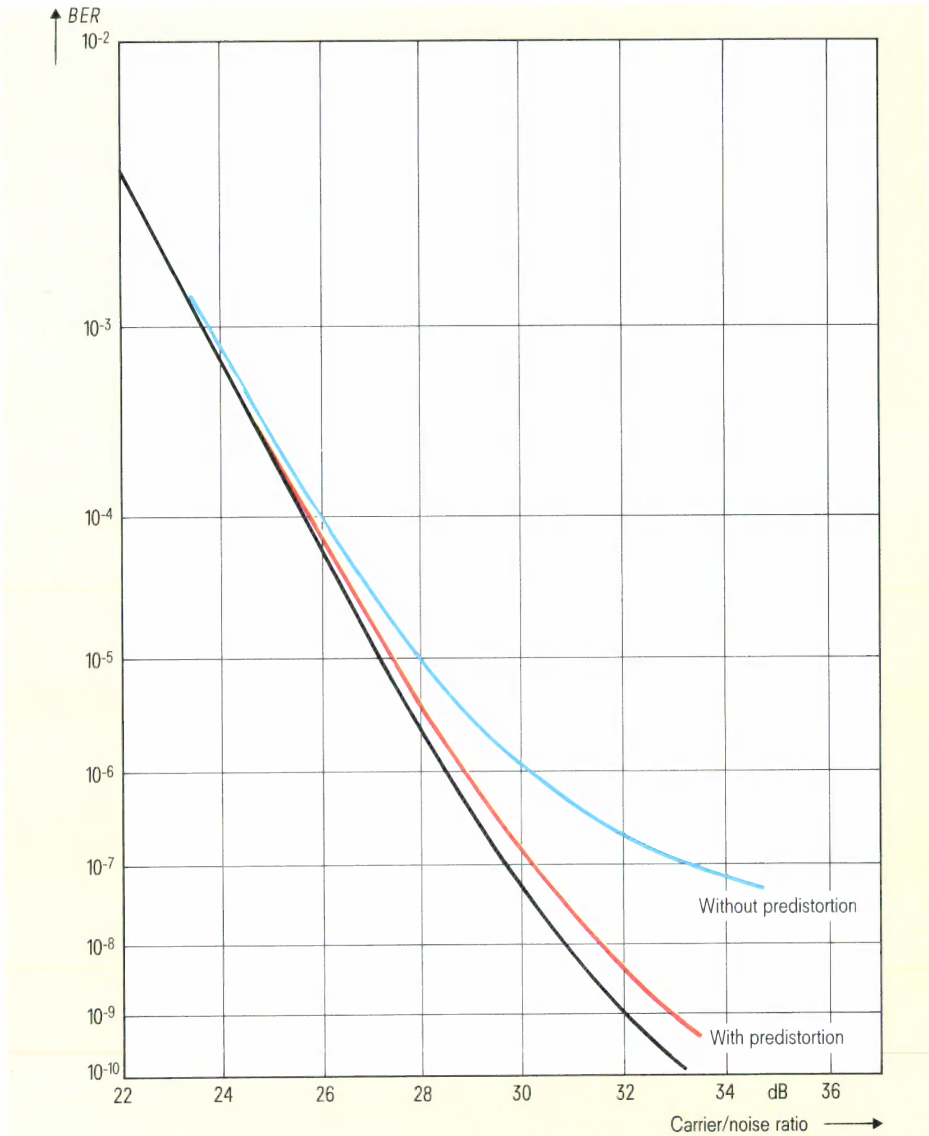

Fig. 9 Predistortion improvement for 64-QAM system with GaAs FET SSPA; output power 33.0 dBm and 24.0 dBm (as a reference)

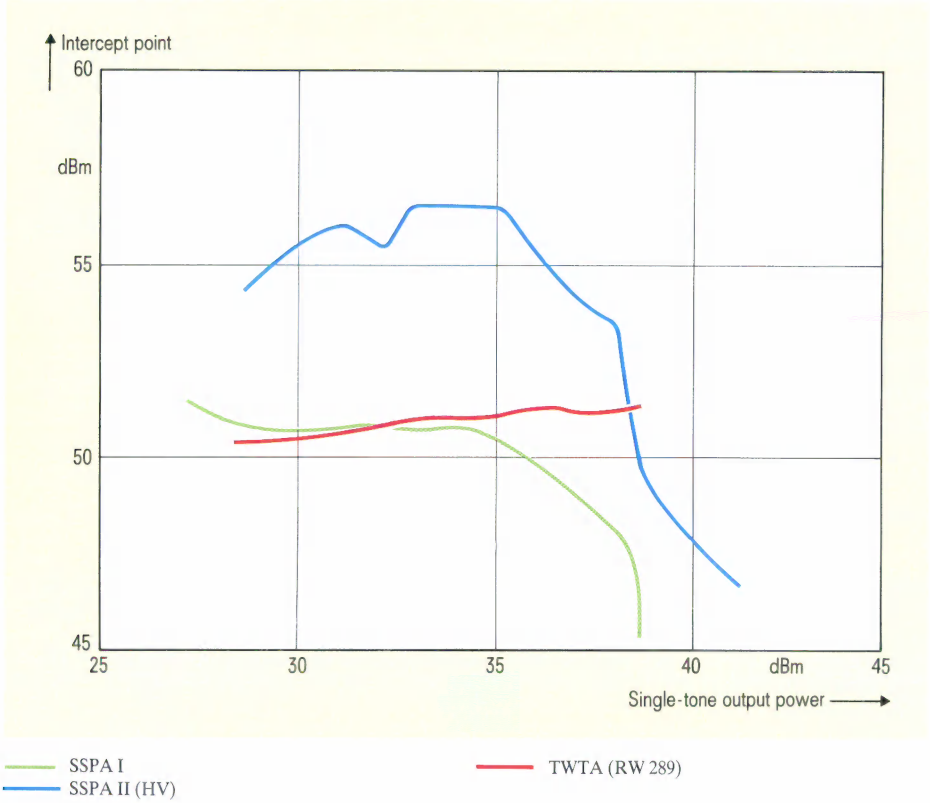

Fig. 10 Third-order intercept points versus single-tone output power for SSPAs equipped with standard and high-voltage GaAs FETs

High-voltage FETs

It has been suggested theoretically and verified experimentally that the linearity of GaAs FETs can be improved by tailoring the doping profile in the active region of the device. Pucel [9] predicted two distinct profiles which should ideally eliminate third-order distortion; a buried spike profile and a graded profile in which the doping fell as $1/x^3$ from the surface. The advantages of graded profiles were also predicted and confirmed experimentally [10, 11, 12]. The above studies used a range of profile shapes and methods to achieve the profiles, such as ion implantation and epitaxy. In addition all reported significant improvements in third-order intermodulation distortion with increasing drain bias voltage. Hence, it can be argued that a FET specifically designed to operate at high drain bias voltages should exhibit improved third-order intermodulation distortion.

To take advantage of this phenomenon, a range of high-voltage FETs has been developed by the Microwave Semiconductor Corporation (USA) using the approach suggested by Wemple et al [13]. Gate-drain avalanche breakdown sets an upper limit on the drain bias that can be applied to an FET. However, the avalanche breakdown voltage can be increased by a factor of 2 to 3 above bulk breakdown by controlling the charge between the gate and drain. In practice this charge control is achieved by a double gate recess process. Using this approach, gate-drain breakdown voltages in the 30- to 50-V range can be achieved routinely, thus allowing FET operation at drain bias voltages significantly above the 10 V of standard commercially available devices.

In an amplifier structure similar to that described, the standard parts in the driver and final stages have been replaced by high-voltage devices with a comparable gate periphery developed by the Microwave Semiconductor Corporation. When operating at a drain voltage of 12 V, this amplifier had a 1-dB compression point of 41 dBm. The measured variation of the (calculated) third-order intercept point versus output power is shown in **Fig. 10**, together with results for the standard device amplifier.

This figure demonstrates a 5-dB improvement in intercept point, which corresponds to an intermodulation ratio about 10 dB higher at a given power level. This improved amplifier has considerable potential for future 64- and 256-QAM systems.

C/N	Modulation format	Available output power at a *BER* of		
		10^{-4} (dBm)	10^{-6} (dBm)	10^{-8} (dBm)
0.2	16 QAM	34.7	33.6	33.2
	64 QAM	34.3	32.1	31.1
0.5	16 QAM	5.8	34.6	34.1
	64 QAM	35.1	33.1	31.9
1.0	16 QAM	36.8	35.4	34.8
	64 QAM	35.8	34.1	32.5

Table 3 Available output power for various *C/N* degradations in a 10-W GaAs FET amplifier

Conclusions

The behavior of state-of-the-art power amplifiers for high-capacity digital radios using 16 QAM and 64 QAM has been presented. The output power available from high-linearity GaAs FET amplifiers is continuously improving, approaching the performance of TWTAs. GaAs FET power amplifiers with a 1-dB compression point of around 10 W can reliably produce output power levels for 64 QAM in the 1-W range without predistortion and in the 2-W range with predistortion.

Improvements in amplifier linearity by the use of high-voltage GaAs FETs have been demonstrated. Together with sophisticated linearization methods, such as adaptive predistortion techniques, amplifiers equipped with these devices can provide sufficient linearity and output power capability at reasonable values of power consumption. Thus, SSPAs also have the potential to become the standard solution for 64-QAM radios operating below 10 GHz, similar to the

existing situation for 16-QAM radios. For future 256-QAM radios, a stimulating competition between SSPAs and TWTAs can be expected.

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Hermann Barth, Manfred Molin, Anton Schröcker and Hans-Otto Simon

Protection Switching Equipment for Digital Radio Relay Links

The 34- and 140-Mbit/s radio relay systems employ an (*N*+1) protection switching system which provides one protection channel for *N* operating channels. The protection switching system is of modular design and can be progressively expanded to a maximum of *N* = 14. For each operating channel provided, a switching inset is required at terminal stations. The inset basically contains a branching circuit for the transmit side and a hitless switch for the receive side. This enables signals to be changed over free of slips or bit errors. The protection switching system is controlled by control insets at the ends of the switching sections. These insets are interconnected via extra control signal channels. In general, dedicated radio relay service channels are used for this purpose.

In less densely populated areas, it may be useful to have access to an operating channel signal within an (*N*+1) protection switching section. Using the hitless switch and an additional drop/insert control unit, this can be provided while maintaining standby channel protection.

For radio relay links with only one operating channel and one standby channel there is a (1+1) protection switching equipment available. In this configuration, the same switching inset is used in conjunction with a simplified control inset.

The authors describe the implementation and design of the (*N*+1) and (1+1) protection switching equipments for digital radio relay systems.

Like their analog counterparts, digital radio relay links are effectively protected by a protection switching system. Apart from providing effective equipment protection and enhanced availability through frequency diversity, another important facility is the removal of traffic from a circuit for maintenance purposes. This facility is of significance due to the use of a hitless switch which enables all prearranged changeovers to be completely free of slips and bit errors.

Sudden equipment faults are reliably protected against by an automatic switchover. Continuous monitoring of the parity comparison indicates an incipient equipment failure. When a suspect unit is replaced as a preventative measure, the relevant circuit can be transferred to the standby channel without interrupting traffic. In higher-capacity systems, space diversity is employed to increase availability, and the units are provided with frequency, and time-domain equalizers [1]. The frequency diversity effect of the protection switching equipment enhances the availability still further [2].

If only one operating channel is protected by a standby channel (space or frequency diversity), it is always possible to utilize the "better" transmission path using the hitless switch without frequent switching causing disturbances.

With digital transmission, a variation in the number of bits between the frame alignment signals results in loss of alignment in the following demultiplexer,

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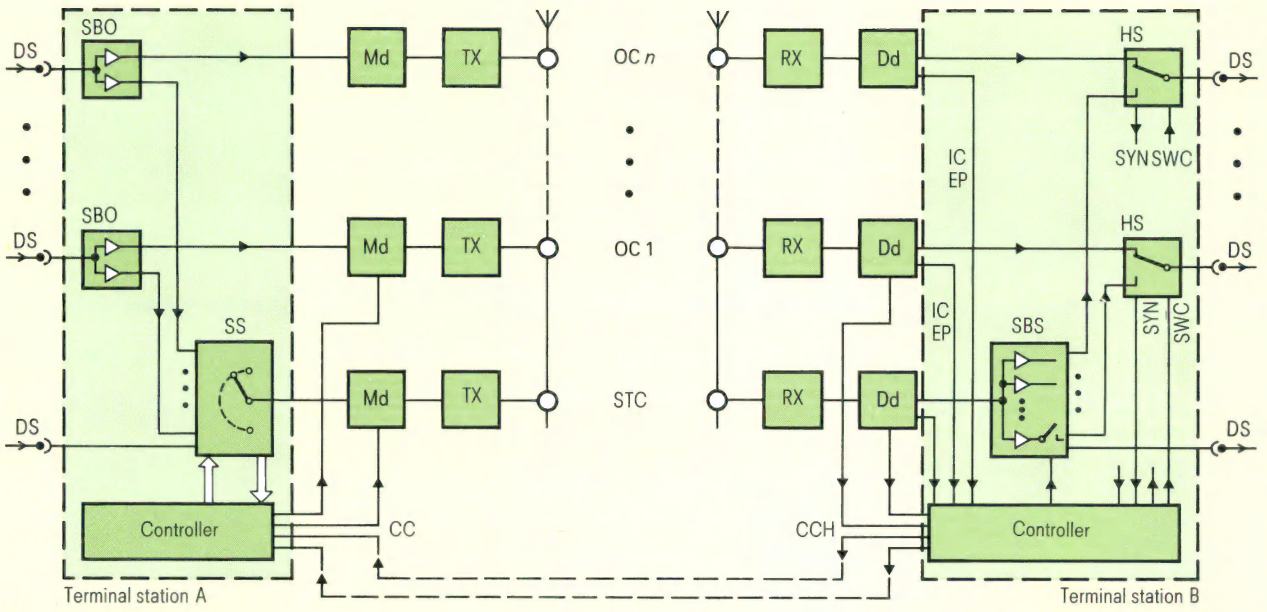


CC	Control channels	Md	Modulator	SS	Signal selector
Dd	Demodulator	*n*	Channel nos. 1 to 7 (14)	STC	Standby channel
DS	Baseband digital signal	OC	Operating channel	SWC	Switching command
EP	Error pulse (parity check)	RX	Radio-frequency (RF) receiver	SYN	Alignment indication
HS	Hitless switch	SBO	Signal brancher, operating channel	TX	RF transmitter
IC	Interruption criterion	SBS	Signal brancher, standby channel		

Fig. 1 Configuration of a protection switching equipment, showing one direction and only the terminal stations

and transmission is interrupted until the demultiplexer has regained alignment. On radio relay links, fading initially causes a deterioration in transmission quality leading eventually to an interruption. If a high-speed quality monitor were used to switch, without a slip in bit count, to a better standby channel before the signal is interrupted, it would be possible to avoid an interruption altogether. This prospect has led to the development of a protection switching technique free of bit errors and slips, in which any delay difference between the operating and standby channel signals is automatically equalized prior to transfer or restoral. This hitless switching technique is also useful for all manually initiated switching operations.

When there are no faults requiring changeover, the "through-connected" standby channel is used to transmit a low-priority signal. Thus, the full system capacity is available for most of the time.

N+1 protection switching equipment

Fig. 1 shows the basic design of an $(N+1)$ protection switching system. Each operating channel (OC) input is assigned an active signal branching circuit (SBO) with the branching point prior to any active element. One output signal from the branching circuit is fed to the terminal modulator of the operating channel, the other to a signal selector which selects an OC signal and passes it on to the terminal modulator of the standby channel (STC). A switch position is provided for STC through-connection. This switch is controlled by the control inset of terminal station A. When there are no faults requiring changeover and the standby channel is not through-connected for any other purpose, this channel carries an OC signal.

At receiving terminal station B, the OC signals are fed directly to their electronic switches. The STC signal is fed via a multi-way signal branching circuit (SBS) to the secondary inputs of the switches; a switchable branching path forms the STC through-connection path.

All the switches attempt to align their two input signals. The only one to succeed in doing so will be the switch in the operating channel whose signal is also being transmitted via the standby channel. When the OC and STC signals have been aligned, this switch transmits an alignment signal (SYN) to the terminal station B control inset which initiates hitless switching if required.

The OC signal branching circuit is combined with a hitless switch to form an OC inset, while the signal selector is combined with the STC signal branching circuit to form an STC inset. Each of these insets is used at switching section terminal stations to serve both transmission directions of the associated operating or standby channel.

Supervision of the radio relay link

Analog radio relay links are monitored for interruptions using a continuity pilot. Quality is monitored by measuring noise in the upper end of the baseband.

High-capacity *digital radio relay links* use a radio relay frame inserted at the terminal station for monitoring purposes [3]. The frame alignment signal and a parity bit are used to check for interruptions and quality, respectively. If no radio relay frame is provided, it is necessary to resort again to a pilot signal for interruption monitoring. In this case it is convenient to monitor quality using the eye opening [4]. In both cases, the criteria are generated in the radio units. These supply an interruption criterion for each RF channel to the control inset and pulses of lesser or greater density depending on the bit error ratio. For each operating channel, the control inset has a 16-bit up/down counter which compares the instantaneous error pulse density with the pulse stream from an oscillator. If the error pulses predominate, the quality alarm is initiated. The alarm threshold and hysteresis can be matched to the characteristics of the link – e.g. it is possible to select a bit error ratio of 5×10^{-6} as alarm threshold and 1×10^{-6} as the restoral threshold.

Control inset

The two terminal stations of a protection switching section employ the same type of control inset (**Fig. 1**). The two insets are interconnected via dedicated control channels (CC). A microprocessor logic circuit receives the criteria of all the incoming channels, evaluates and links them with any manual commands present, so that a switching sequence is initiated for one operating channel only, even in the event of multiple errors. For this purpose, the control inset of terminal station B transmits a message to the control inset of terminal station A, which causes the standby channel to be bridged to the operating channel selected. On receiving confirmation that the transmit-end signal selector in the standby channel has been correctly set, control inset A sends back a verification message. On receipt of the latter, the control inset of terminal station B changes over the receive-end switch. If the request for changeover is not due to signal interruption, the alignment signal from the hitless switch is additionally taken into account. The status of all the channels is continuously displayed with LEDs.

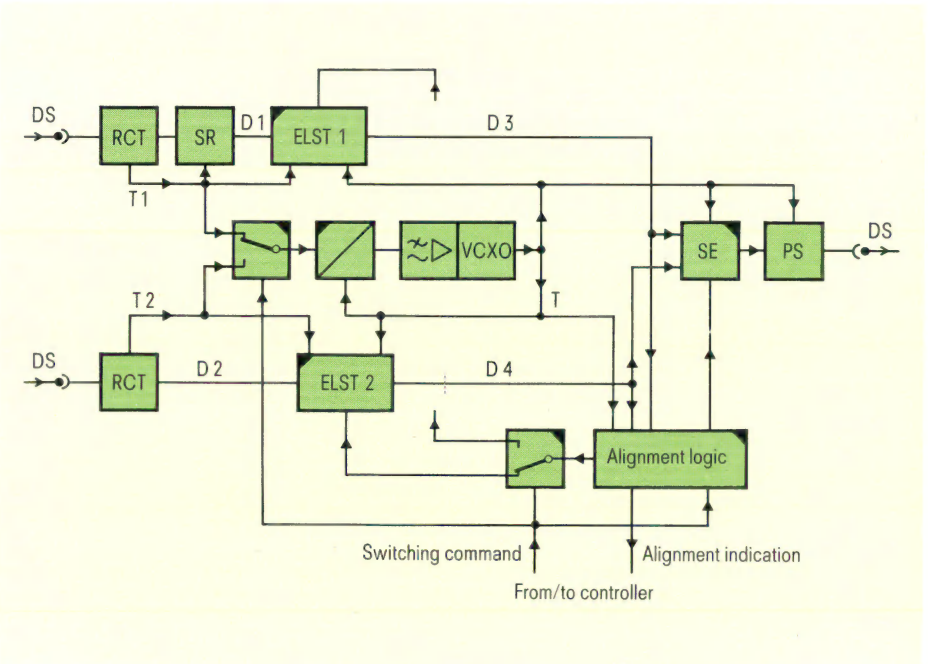
Control link

As correct operation of the $(N+1)$ protection switching equipment depends on a reliable exchange of information between the two controllers, the transmission of control messages is protected in both directions by an independent $(1+1)$ protection switching system (**Fig. 1**). The facilities for this purpose are likewise accommodated in the control insets. The messages are protected against transmission errors by a redundant "2-out-of-8" code. Furthermore, two consecutive messages have to be equal in order to generate a switchover command. Only those verification messages are accepted which represent a correct response to the previously transmitted command message. Messages can be transmitted on both analog and digital channels. In the former case, the message is FSK-modulated, in the latter case, it is transmitted in binary form without further modulation. Usually, the radio relay units to be protected and their associated service channels offer sufficient capacity to include transmission of the control messages [5].

Hitless switch

When a fade occurs in an operating channel and the quality threshold is exceeded, the control inset bridges the standby channel to the channel affected. The same signal is then present at both inputs of the hitless switch in the disturbed operating channel, and an alignment process can commence.

For this purpose, the incoming signals in HDB3 code (high density bipolar of order 3) at 34 Mbit/s or CMI (coded mark inversion) at 140 Mbit/s are regenerated in the interface, converted to binary NRZ (nonreturn to zero) signals (D1, D2) and read into their respective elastic stores with the associated timing signals (T1 and T2, respectively) (**Fig. 2**). The two signals are read out using the timing signal, T, of a voltage-controlled crystal oscillator (VCXO) which is locked by a phase-locked loop to the timing of the signal through-connected at the particular time. It is now possible to make a bit-for-bit comparison of the two signals, D3 and D4, in the alignment logic circuit which provides a criterion for their alignment. If a counter for the bit inequalities becomes full within a specified time, alignment is assumed to have been lost; signal, D4, is



	140 Mbit/s gate array	RCT	Interface, regenerator, code converter timing recovery
D	Digital signal, binary	SE	Switch, encoder
DS	Baseband digital signal in line code	SR	Shift register, adjustable
ELST	Elastic store	T	Timing signal
PS	Pulse shaper	VCXO	Voltage-controlled crystal oscillator

Fig. 2 Functional diagram of a hitless switch

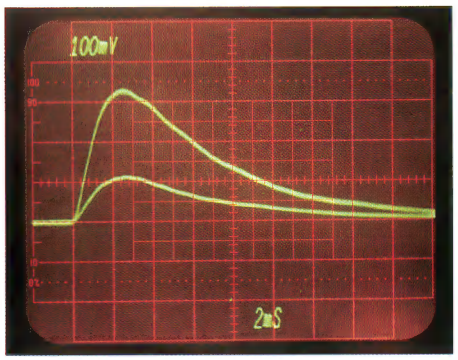
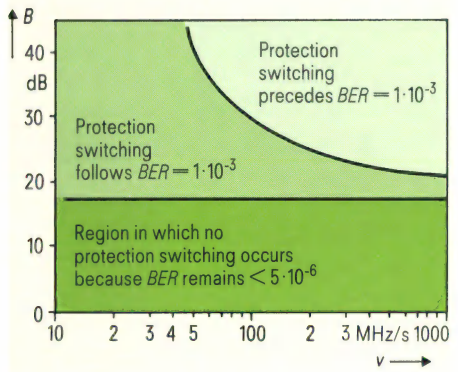


Fig. 3 Curves of the output jitter following hitless switching of a 140-Mbit/s signal: delay difference 14.4 ns (≙ 2 bit) – lower curve; delay difference 43 ns (≙ 6 bit) – upper curve; horizontal: 2 ms per scale division and vertical: 0.3 UI (unit interval)



B	Notch depth of a two-path simulator
BER	Bit error ratio
v	Notch velocity

Fig. 4 Protection switching of the (*N*+1) system, as a function of notch depth and notch velocity of a two-path simulator

adjusted by the alignment logic altering the writing address of elastic store 2 in the standby path, and the monitoring sequence is restarted. Alignment is achieved within 50 µs; it is reliably detected up to a bit error ratio of greater than 1×10^{-3}. After the two signals have been aligned, it is possible to switch from the operating to the standby path during the data transmission completely error-free.

If there is a delay difference between the two input signals, D1 and D2, timing signals, T1 and T2, also exhibit a phase displacement. After switching has taken place, the timing signal, T, of the voltage-controlled crystal oscillator previously locked to T1 must adjusted to the timing signal, T2, of the now through-connected digital signal, D2. The phase change which T undergoes during this process of adjustment reappears as jitter on digital signal, D4, as it is read out. The value of this jitter must remain within the limits specified in CCITT Recommendation G.703. The very narrow loop filter of the crystal-oscillator control loop limits the jitter amplitude to permissible values.

As restoral from the standby channel to the operating channel is effected in the same way, it is also hitless.

In order to monitor the complex circuit sections of the switch, the controller periodically initiates an alignment process, without switchover, when the standby channel is idle. This process must be successful within a specified time, otherwise an alarm is signaled.

In the 140-Mbit/s version of the switch, the circuit sections identified in **Fig. 2** are concentrated in a large-scale integrated emitter coupled logic (ECL) circuit in gate array technology.

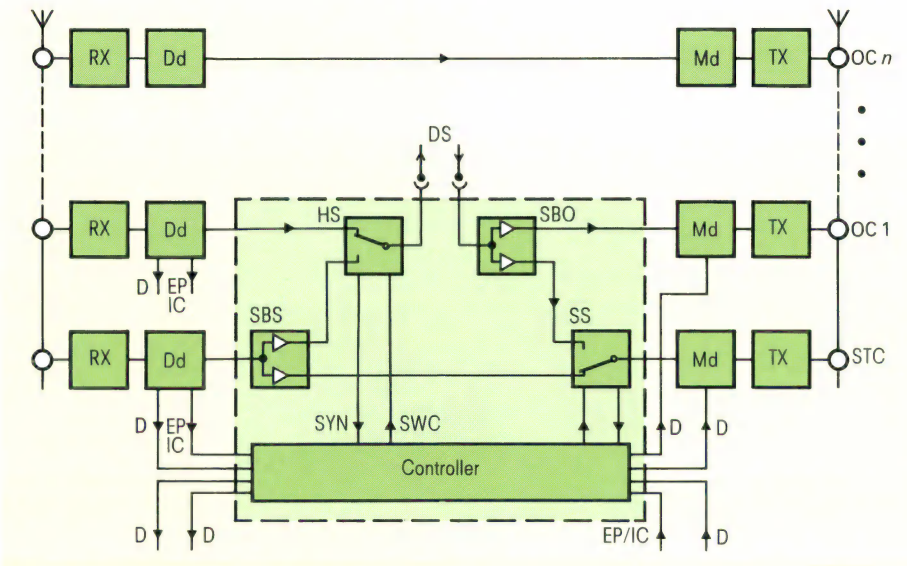
Fig. 3 shows the time characteristic of the output jitter of a 140-Mbit/s signal, as measured using a weighting filter in accordance with CCITT Recommendation G.703 at the switch output following a changeover. Whereas the lower curve shows the output jitter for a delay difference of 14.4 ns (≙ 2 bit), the upper curve gives the output jitter for the extreme delay difference of 43 ns (≙ 6 bit). Even with this large delay difference, the jitter still remains below the permissible value of 1.2 UI (unit intervals).

Fig. 4 shows the velocity at which an attenuation maximum (notch) due to a two-path fade [6] may penetrate the wanted band and still allow an interruption-free changeover.

If the notch passes through the frequency band of two or more RF channels, each channel affected is switched to standby in turn, without interruption, up to a velocity of some 50 MHz/s and independent of the notch depth.

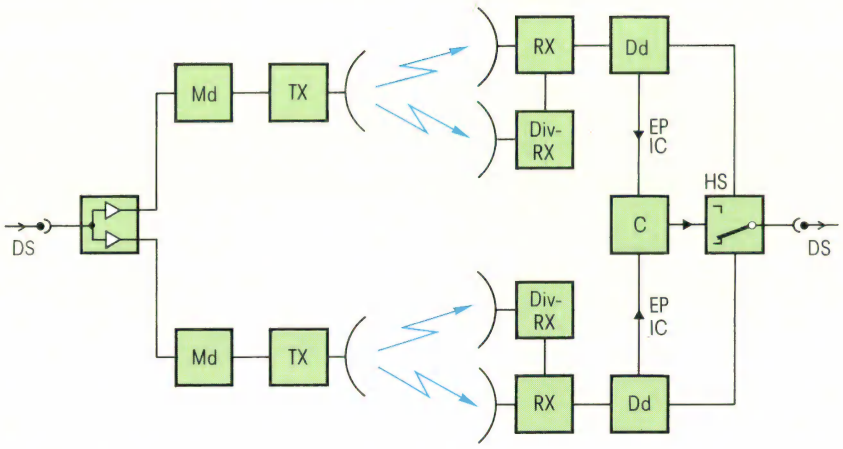
Drop/insert

Over the length of an (*N*+1) switching section it may become necessary at several repeater stations to drop the signal from an operating channel and to insert a new one, without completely subdividing the switching section at the particular repeater station (**Fig. 5**). As this sub-



D	Service channel, digital	RX	RF receiver
Dd	Demodulator	SBO	Signal brancher, operating channel
DS	Baseband digital signal	SBS	Signal brancher, standby channel
EP	Error pulse (parity check)	SS	Signal selector
HS	Hitless switch	STC	Standby channel
IC	Interruption criterion	SWC	Switching command
Md	Modulator	SYN	Alignment indication
n	Channel nos. 1 to 7 (14)	TX	RF transmitter
OC	Operating channel		

Fig. 5 Functional diagram of a repeater station with drop/insert; one direction shown



C	(1+1) control inset	HS	Hitless switch
Dd	Demodulator	IC	Interruption criterion
Div-RX	RF diversity receiver	Md	Modulator
DS	Baseband digital signal	RX	Main RF receiver
EP	Error pulse (parity check)	TX	RF transmitter

Fig. 6 (1+1) protection switching with space and frequency diversity; (one direction shown)

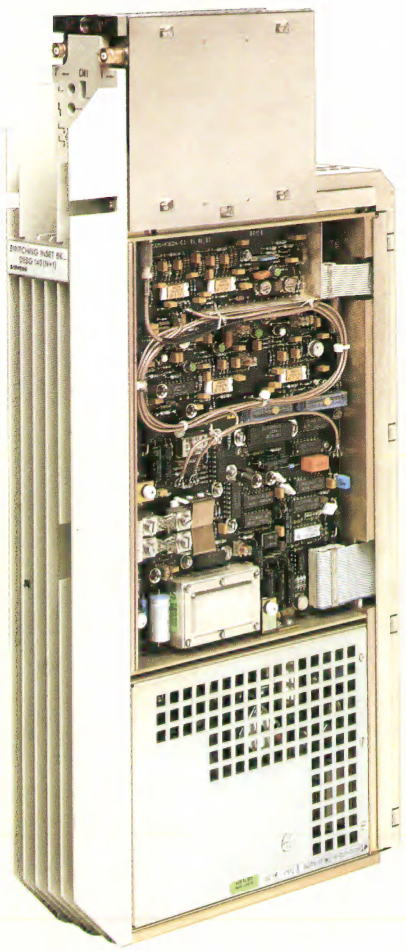


Fig. 7 Side view of the operating channel (OC) inset

divided operating channel still has to be protected by the standby channel, it follows that the standby channel must also be subdivided.

The information of the terminating radio relay frames must be detected and transmitted in a service channel of the subsequent section to the $(N+1)$ controller, so that the latter knows the status of the subdivided channels in the entire protection switching section. If required, the $(N+1)$ controller then causes the entire subdivided channel to be switched to standby, the switching equipment at the drop/insert station being actuated by the $(N+1)$ controller via the drop/insert control unit. A prearranged changeover is again effected without bit errors or slips.

1+1 protection switching equipment

A special form of the $(N+1)$ protection switching equipment is the (1+1) equipment. With the latter, the signal to be protected is continuously transmitted via two channels, and the receive switch constantly reports alignment of the received signals when possible (**Fig. 6**). Since completely hitless switching is possible for signals in alignment, changeover is effected immediately even if the signal path currently through-connected merely has a parity error. In order to prevent excessive switching, no parity error must have occurred in the other channel within about 100 ms previously. If bit errors occur in both signal paths simultaneously, a comparison logic circuit selects the better path for transmission.

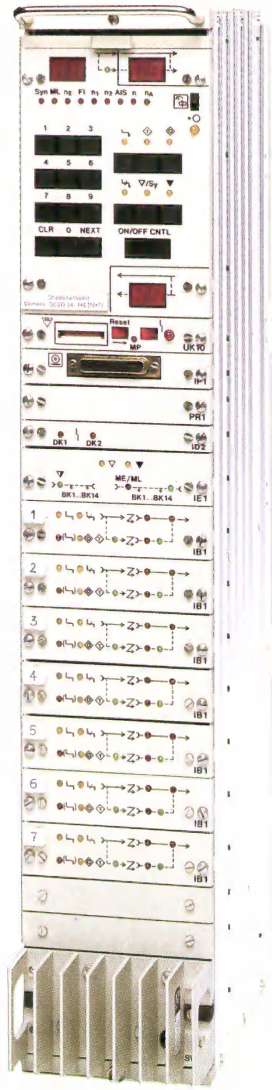
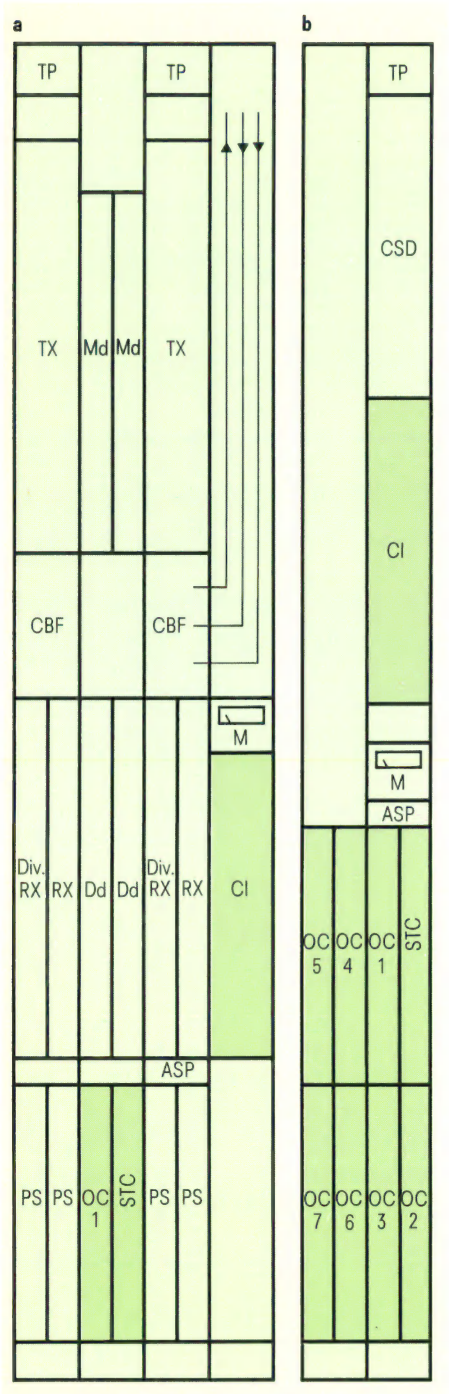


Fig. 8 Front view of the (*N*+1) control inset

The switching process is monitored by a control inset which is only provided for the (1+1) protection switching equipment.

This concept has significant advantages for extremely long hops. As depicted in **Fig. 6**, each signal path can first be provided with space diversity. If frequencies from different RF bands are selected for the two channels, the frequency diversity effect considerably improves transmission [2].



ASP	Alarm signal panel
CBF	Channel branching filter
CI	Control inset $N+1$
CSD	Coaxial splitter distributor
Dd	Demodulator
Div-RX	RF diversity receiver
M	Meter
Md	Modulator
OC	Operating channel inset
PS	Power supply
RX	Main RF receiver
STC	Standby channel inset
TP	Terminal panel
TX	RF transmitter

Fig. 9 Mounting options for protection switching equipments in 2.60 m high style 7R narrow racks; integrated arrangement of the insets of an (N+1) protection switching system (a); arrangement of protection switching units in separate switching racks (b)

Mechanical design

Like the radio relay systems themselves, the switching equipments are designed in style 7R. The OC and STC insets as well as the (1+1) control inset are of Type 3 [7]. In the shielded switching inset housings, the circuit board mount consists of an aluminum I-section which provides good heat dissipation to the cooling fins on the front panel. The insets are enclosed with covers at the sides (**Fig. 7**). Owing to the large number of control and signaling line connections, as well as the need to allow for reconfiguration to suit system expansion, inset Type 2 [7] was selected for the (N+1) control inset and for the drop/insert control unit (**Fig. 8**).

The power supplies are integral with the individual insets. In the OC switching inset, two power supplies operating on a redundancy basis are provided in order to increase the reliability of the switching equipments. Thus, each unit can be replaced without interrupting traffic.

When installing the insets, it is possible to opt for either an integrated configuration in the radio relay system racks or a system-independent configuration in separate switching racks.

Fig. 9a shows the integrated arrangement of the insets of an (N+1) protection switching unit in radio relay sytem DRS 140/6700. (1+1) protection switching systems are always installed in the modem rack. The (1+1) control inset then takes the place of the STC switching inset which is not required for (1+1) protection switching. In this type of configuration, the insets are connected by prefabricated coaxial lines and multiconductor system cables.

Fig. 9b shows the units mounted in separate switching racks. The racks are prewired; the coaxial lines are provided according to the capacity stage. The coaxial splitting distributors in the upper part of the racks ensure both easy access to the station cable connections during installation, as well as easy splitting for test purposes.

Summary

Digital radio relay links, like their analog counterparts, are provided with protection switching equipment in order to increase their availability. Unlike protected analog links, digital links are able to use a hitless switch which permits completely disturbance-free switching. This is useful not only for removing traffic from a circuit for maintenance purposes; it also provides both increased availability and improved quality particularly on a (1+1) system, and especially if protection switching is initiated in response to criteria detected even before bit errors occur. This provides another effective means of increasing availability in addition to space diversity [1] and adaptive equalization [3]. For this purpose, suitable criteria produced by the radio and modem equipments can be used for "early detection."

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Service Channel Unit and Utilization of Digital Service Channels

High-capacity digital radio relay equipments employ a radio relay frame for supervising the link. This frame can be additionally used to provide service channels in digital form for no significant extra cost and without degrading the main signal.

Many PTT administrations use these service channels for voice communication between the radio relay stations (EOW engineering order wire) and for transmitting supervisory and control signals. Similarly, the data generated locally at a station for quality and reliability analysis can be transmitted via service channels to a terminal station for processing at a central location. The remaining service channel capacity can be used to provide telephone connections along the route (wayside traffic).

This article reports on a flexible service channel unit enabling the required services to be provided economically via the digital service channels and permitting expansion without interrupting service. In order to protect the service channel signals, it also combines the service channels of two radio frequency (RF) channels in an independent (1+1) protection switching facility.

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On wideband radio relay links, it is advisable to provide several service channels (SC) in parallel with the operating channels to meet the needs of operation and maintenance personnel for voice communication between the radio relay stations (EOW). The station alarms gathered from the remote supervision units require transmission to the central location at a terminal station. Where the radio relay link crosses sparsely populated territory it may be advantageous to provide individual telephone connections without using the baseband signal of the link (wayside traffic). This approach provides very low-cost connections to the public telephone network.

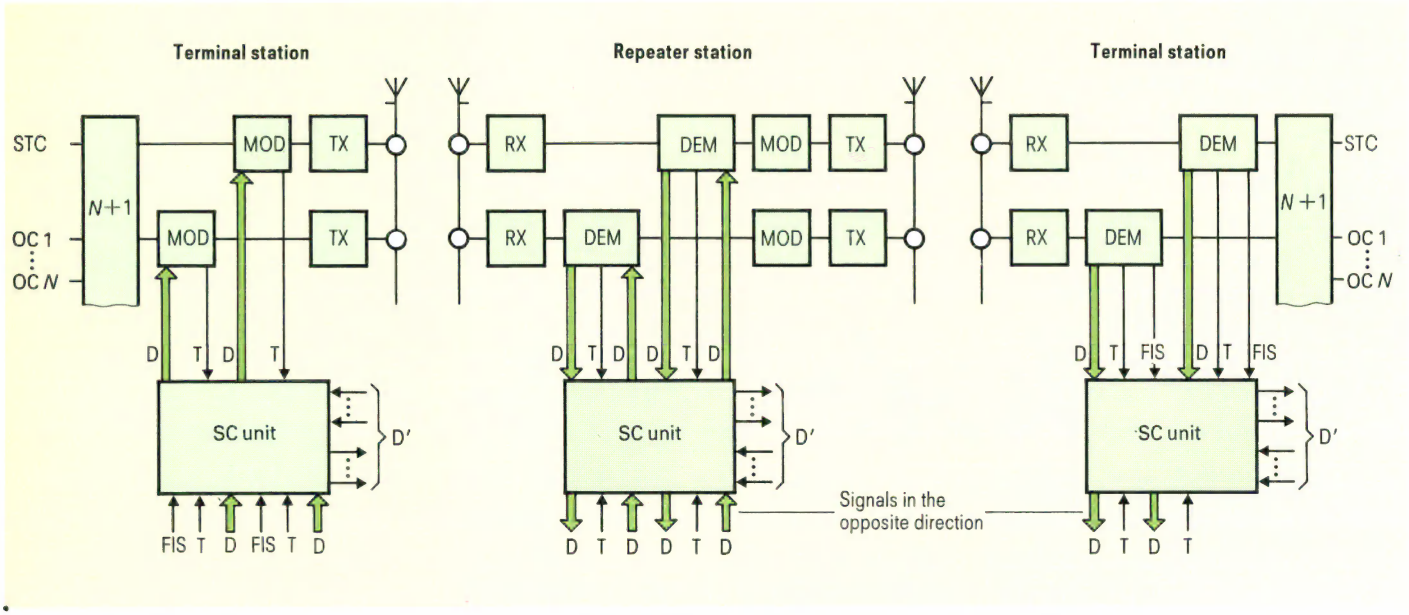
On analog FM (frequency modulation) radio relay links, the signals of these services were normally transmitted in the frequency band below the baseband (subbaseband technique). On digital radio relay links, it would be possible to transmit such service signals on the modulated carrier by using frequency modulation. However, this frequency modulation is a source of interference to the quadrature amplitude modulation (QAM) employed on such links, and produces undesirable degradation particularly on 16 and 64 QAM. In order to avoid such degradation, high-capacity digital radio relay systems are equipped with digital service channels, enabling the required services to be provided [1]. The service channel unit (SC unit) with analog-digital converters is used for this purpose in establishing the link between the service signals, which are normally in analog form, and the digital form of signal required for transmission.

For certain channels, the SC unit incorporates a selective calling equip-

Service channels of the DRM 140/140 modem		Demultiplexing in in the service channel unit	Services transmitted
No.	Bit rate		
		34.5 kbit/s	Omnibus service signal
		34.5 kbit/s	Express service signal
SC 1	138 kbit/s	69 kbit/s	High-grade omnibus service signal or RS signal
		or	
		2 × 34.5 kbit/s	RS signals
SC 2	138 kbit/s	4 × 34.5 kbit/s	Wayside traffic (four channels)
			or
			Data signals, contradirectional or asynchronous, CCITT Rec. V.11/V.28 (four channels)
		or	or
		2 × 69 kbit/s	64-kbit/s signals, CCITT Rec. G.703 (two channels)
SC 3	138 kbit/s	Same as SC 2	Same as SC 2
SC 4	34.5 kbit/s	–	E&M signals
SC 5	34.5 kbit/s	–	Messages for (1+1) protection switching of SC unit

E&M Exchange and multiplex RS Remote supervision SC Service channel

Table Digital service channels of the DRS 140/... systems



D	Service signal, digital	*N*	Number of channels 1 to 7 (14)	SC	Service channel
D′	Service signal for user, analog or digital	*N*+1	Protection switching equipment	STC	Standby channel
DEM	Demodulator	OC	Operating channel	T	Timing signal
FIS	Fault indication for SC disturbed	RX	Radio relay receiver	TX	Radio relay transmitter
MOD	Modulator				

Fig. 1 Insertion of the service channel unit in a radio relay link – only one direction shown

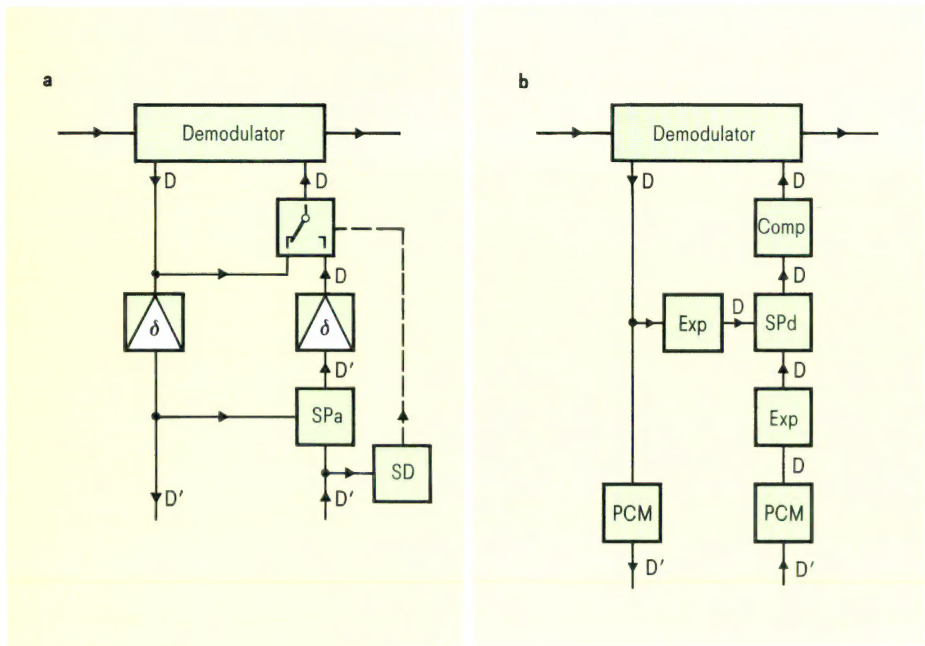
ment for addressing specific radio relay stations. A specially built-in (1+1) protection switching facility protects all the transmitted services against interruption.

Radio relay frame and service channel capacity

The radio relay frame, used to supervise the link for interruptions and quality, provides not only for the transmission of system and hop-related information but also of digital service channels. For this purpose, the radio relay frame inserted in the 140-Mbit/s baseband signal by the terminal station modulator, for instance, passes through the entire switching section and is not extracted until it reaches the terminal station demodulator. However, the regenerating repeater station demodulators allow the service channel bits in the radio relay frame to be overwritten in order to provide omnibus channels. If a radio relay link is interrupted, the next operable repeater station modulator following the interruption switches automatically to terminal operation and forms a new radio relay frame. It is thus possible for supervision and service channel transmission to continue on the rest of the link.

The **Table** lists the service channel capacities of the DRS 140/... radio relay systems described in [2] as an application summary.

On objective in the design of the radio relay frame was to prevent the frame from causing justification jitter on insertion in the 140-Mbit/s baseband signal. As a result, the framing rate ceases to be freely selectable and a standardized bit rate for the service channels of, for instance, 64 kbit/s cannot be achieved



Comp	Compressor	PCM	PCM modem
D	Service signal, digital	SD	Signal detector
D′	Service signal, analog	SPa	Superposition, analog
δ	Delta modem	SPd	Superposition, digital
Exp	Expander		

Fig. 2 Service signal through-connection at repeater stations with superposition of local service signals
a Analog service signal superposition
b Digital service signal superposition

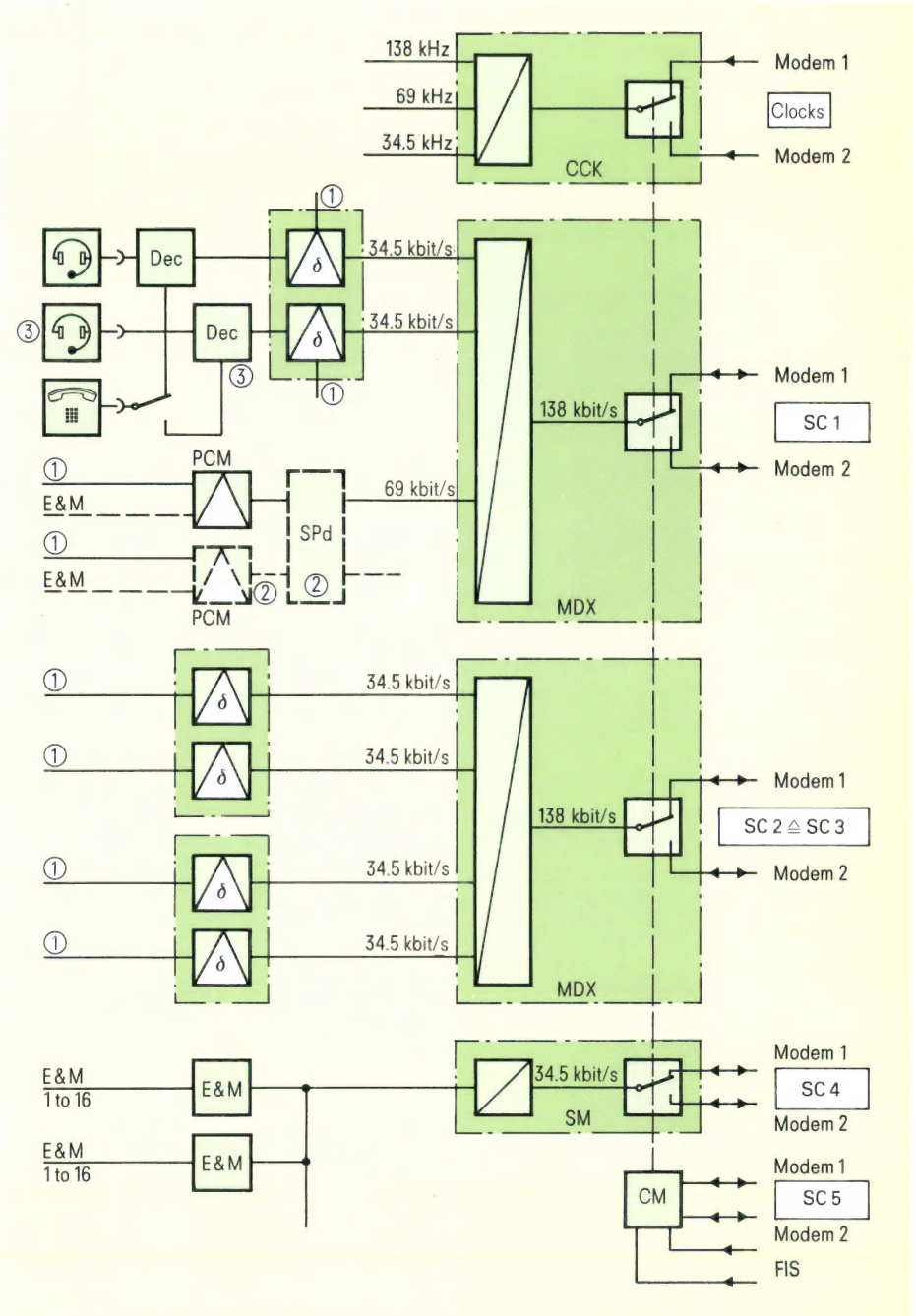
directly. For the services provided with the service channel unit this is, however, an advantage since capacity is retained for the provision of a service channel justification frame (e. g. 69-kbit/s service channel bit rate for the 64-kbit/s standard bit rate with codirectional interface in accordance with CCITT Recommendation G. 703).

Since the radio relay frame is in synchronism with the baseband signal, the bit rate tolerance permitted by CCITT Recommendation G. 703 is transferred to the service channel bit rate of the radio relay modems. For this reason, analog-digital conversion is performed in the SC unit with a timing signal supplied by the modem. The digitized service signals are transferred to the modem via a contradirectional interface, again in accordance with CCITT Recommendation G. 703. The interface itself is of balanced design for TTL levels in accordance with CCITT Recommendation V. 11. The number of interconnecting lines is reduced by transferring 3 × 138 kbit/s and multiplexing them in the SC unit, in addition to a single 34.5-kbit/s line.

Inserting the service channel unit in a radio relay link

The interconnection of the service channel unit to the radio relay units at terminal and intermediate stations is shown in **Fig. 1**. Each station is provided with a unit of this type and the service channel signals pass through it in both transmission directions. At repeater stations, the service signals are extracted and inserted at the demodulator. For enhanced service reliability, these signals can be transmitted in each direction via two RF channels. The associated service channels are protected by a (1+1) protection switching facility incorporated in the service channel unit. The (1+1) protection switching facility obtains its switching criteria from the terminal station demodulators. A fault in a service channel unit at a repeater station causes the service channels to be through-connected in the associated demodulators in order to maintain service channel operation.

The service signals are transmitted via balanced VF lines with 600-Ω impedance and a standard level of −14(−13)/+4 dBr, and which can be reset to −4/−4 dBr for through-connection.



Headset with microphone
Handset
① Standard VF (voice-frequency) interface
② At repeater stations only
③ At terminal stations only
CCK Central clock
CM (1+1) control module
Dec DTMF decoder (dual tone multifrequency)
δ Delta modem
E&M E&M interface (exchange & multiplex)
FIS Fault indication for SC disturbed, used at terminal stations
MDX Multiplexer/demultiplexer
PCM PCM modem
SC Service channel
SM Signaling multiplexer
SPd Superposition, digital

Fig. 3 Design of the service channel unit

When service signals are already supplied in digitized form, they can be transferred via a codirectional or contradirectional interface synchronously or – at reduced transmission speed – asynchronously.

Features of digital service channels

Digital service channels have certain features which must be taken into account when using them.

Analog-digital conversion

Normally the service signals for transmission are available in analog form, e.g. voice or FSK signals from remote supervision units (RS). These signals are digitized in delta or PCM modems. With omnibus channels, analog-digital conversion must be performed at every radio relay station, which leads to an accumulation of quantizing noise from all the conversions. The total number of conversions must, therefore, be kept as small as possible and this is achieved in the service channel unit in two ways (**Fig. 2**).

Analog superposition

The digitized service signals at repeater stations are normally through-connected, but this is interrupted when a signal is generated locally or for a sequentially polled remote supervision unit to transmit messages. The link signal received in the delta modem via a digital-analog converter is superposed in analog form on the local signal and is converted with the latter back to a digital signal for onward transmission. This signal thus undergoes no more than two analog-digital conversions on its way from terminal station to terminal station.

Digital superposition

Remote supervision units operating on a different principle (parallel remote supervision units in accordance with CCITT Recommendation H.23) transmit signals constantly. This means that the analog-digital converters at all repeater stations must always be in operation. Nevertheless, in order to minimize the number of individual conversions, the RS signal arriving at a repeater station has the locally generated signal superposed on it in digitized form.

The RS signal digitized at 64 kbit/s in a PCM codec must be expanded before digital superposition and compressed again for onward transmission after the 8-bit words have been added. These processes are synchronized by inserting into the service signal a special frame in which an exchange and multiplex (E & W) signal is also transmitted. The auxiliary frame requires about 5 kbit/s; the transmission rate in the radio relay service channel is 69 kbit/s. This provides a high-grade transmission channel

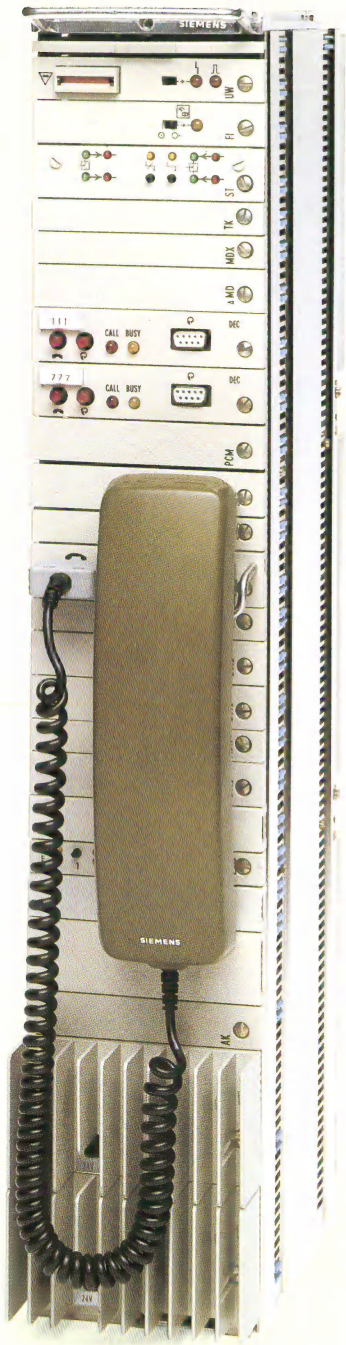


Fig. 4 Style 7R inset (Type III) with plug-in modules forming the service channel unit

in which the RS signal of each station undergoes only one analog-digital conversion in any switching section of a radio relay link.

(1+1) Protection switching

The previously mentioned bit rate tolerance of the radio relay service channels does not allow the service signals to be parallel-fed into the service channels of the two RF channels. The service signals for each direction are processed in the service channel unit with the timing signal of the corresponding RF channel. The digitized service signals can be applied only to this channel via the contradirectional interface. If traffic in this channel is interrupted, switching must occur not only at the receiving stations but also at the transmitting stations. The switching command is generated for this purpose by the (1+1) controller of the receiving terminal station and transmitted to all transmitting stations within the switching section via two SC 5 service channels in the opposite direction.

Service signal through-connection at back-to-back terminal stations

The bit rate tolerance of the radio relay service channels must also be taken into account in through-connecting service signals at back-to-back terminal stations. Signals can be passed on in analog form after digital-analog conversion and further analog-digital conversion using the timing signal of the following service channel. With asynchronous transmission, digital service signals can be readily through-connected at reduced speed. With an additional justification facility (stuffing) it is also possible to through-connect at the standard bit rates of 32 and 64 kbit/s. Two service channel units are always required at back-to-back terminal stations.

Functional description

The modular structure of the service channel unit, enabling it to be configured to suit the particular requirement, can be seen in **Fig. 3**. The individual functions are grouped into modules.

A standard configuration for the first 138-kbit/s service channel (SC 1) of the radio relay modem is shown. It provides an omnibus service channel (omnibus EOW), an express service channel (express EOW) and a high-grade RS channel. Both the omnibus and the express channel are accessible via a switchable handset and via separate headsets with microphones. The handset incorporates the keys for dialing. They are used to generate the dialing signals in accordance with the DTMF system (DTMF dual tone multifrequency) standardized in CCITT Recommendation Q.23 for selectively calling one or more stations. The decoder modules

evaluate the incoming DTMF signals and produce an audible and visual signal on detecting their own number. The analog-digital or digital-analog conversion is then performed with a delta modem device operating on the CVSDM principle (CVSDM continuously variable slope delta modulation) at 34.5 kbit/s. One module combines the components for two VF channels. At repeater stations, the signal detection circuit of the delta modem determines whether an incoming signal in digital form is to be passed on directly in the "multiplexer/demultiplexer" (MDX) module or whether a local voice signal must be superposed in analog form.

The analog RS signal converted in a PCM codec to 64 kbit/s is passed through an elastic store which provides an additional frame to monitor the PCM demodulation and permits digital superposition at a repeater. The additional frame accommodates the E&M signal. The "digital superposition" module is required only at repeater stations where there is a need to superpose incoming and local RS signals.

The "MDX" module multiplexes the two 34.5-kbit/s signals with the 69-kbit/s signal to form a 138-kbit/s signal which is fed via the changeover switch to a radio relay modem. The setting of the switch is monitored by the control module (CM) which also receives and processes the criteria of the associated demodulators. The control module additionally generates the switching command messages for all the other stations (transmitted via two SC5's in the opposite direction).

For the second and third 138-kbit/s service channels (SC2 and SC3), **Fig. 3** proposes a configuration with delta modems. Their function is similar to that described for service channel SC1. These channels can be used for wayside traffic or via PABXs to provide telephone connections.

The 34.5-kbit/s service channel (SC4) is available for transmitting E&M signals. The "signaling multiplexer" in conjunction with four E&M interface modules (two of which can be mounted directly in the SC unit) provides up to 64 E&M channels. They transmit the signaling for the additional telephone circuits, but can also be used for transmitting low-speed indications and commands.

The service channel unit incorporates its own power supply module, furnishing all the internally required operating voltages from a battery input. A second power supply can be used as a redundant power supply for the SC unit.

Apart from the facilities described, some modules can be mounted externally to the SC unit for additional applications, such as

- providing a 64-kbit/s standard interface,
- providing VF four-wire branching,
- providing a remote SC connection via four-wire/two-wire converters,
- connecting a private network with the aid of a PABX interface and
- expanding to 64 E&M channels.

The service channel unit presented thus provides versatile, flexible and economical facilities for utilizing the additional transmission capacity available with multiframed digital radio relay systems (e.g. DRS 140/...).

Mechanical design

The modules of the service channel unit plug into a style 7R inset (Type III) 600 mm high and 110 mm wide [3], as shown in **Fig. 4**. Inside the inset the connector strips of the modules are mounted on a multilayer board. Owing to the various equipping options, the individual module mounting locations have to permit multi-purpose utilization. The SC inset is also of plug-in design and is connected to the station cabling via 84-contact wire-wrap connectors.

Summary

Unlike analog service channels, the digital service channels available on high-capacity digital radio relay systems produce no degradation of the main signal.

The service channel unit described permits flexible and economical utilization of the transmission capacity available in the system multiframe for

- voice communication between radio relay stations (EOW),
- transmission of remote supervision and control signals,
- quality and availability analysis or fault location, as well as for
- telephone connections along the radio relay route (wayside traffic).

The many different uses to which the service channel capacity can thus be put provide an effective aid in operating transmission networks economically and reliably.

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Antennas and Waveguide Components for Radio Relay Systems

The introduction of new radio relay systems in recent years, and in particular the transition from analog to digital techniques, has imposed increasingly stringent requirements on the electrical properties of the antennas employed. The arrangements used up to this time, such as focal-point-fed paraboloids, horn-reflector antennas or directly fed, shell-type antennas, were not capable of optimally meeting these requirements. Furthermore, the demand for a more tightly meshed network, which at present consists of routes operated exclusively with two orthogonal linear polarizations, as well as the increasing problems of installation space on radio relay towers have led to new solutions.

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The most important aspects in the design of the new antennas and transmission line components were:

- higher sidelobe attenuation in all areas of the azimuth radiation pattern outside the main lobe,
- substantially improved cross-polarization properties and
- considerably increased bandwidth, extending to the realization of dual-band antennas which can be operated simultaneously in two frequency bands with two planes of polarization in each band.

Antenna concepts

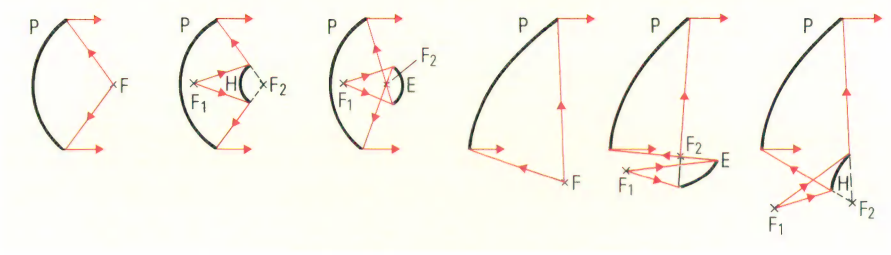
In view of the required high gain and narrow beams, radio relay systems employ almost exclusively aperture antennas, i.e. antennas with a large radiating area. This is formed by a passive reflector illuminated by a suitable primary radiator or a feed system. The feed system itself may incorporate secondary reflectors with conical section curvature, which are located in the far-field or near-field of the radiator. These secondary reflectors may be specially shaped to achieve special characteristics. A selection of typical antenna designs is shown in **Fig. 1.**

All the above mentioned properties are to some degree determined by the electrical quality of the primary radiator, which forms the transition between the signal in a transmission line and free space. Waveguide radiators and conical horn radiators of circular cross section are predominantly employed for the applications referred to. An ideal radiator, which is free from cross-polarization coupling, should have a radiation pattern which is identical in all sectional planes of the diagram, i.e. it should exhibit complete circular symmetry. The customary horn radiator of circular cross section is excited in its fundamental TE_{11} mode. Due to the varying boundary conditions across the aperture, it also exhibits varying field distribution and, consequently, varying radiation patterns with strong cross-polarization components in the diagonal planes.

Many attempts have been made to achieve symmetry in the field pattern. The main methods of proved practical importance are:

- suitable additional higher-order modes superimposed on the fundamental mode (limited bandwidth), and
- excitation of hybrid modes by means of corrugated horns.

Hybrid modes are combinations of TE_{1n} and TM_{1n} modes, which propagate in pairs with equal phase velocities in the horn and thus do not exist in waveguides with smooth walls. For this reason, the conducting inner walls of the corrugated horn are provided over the entire length of the radiator with radial or coaxial machined grooves (**Fig. 2**). With optimum dimensioning, the radiation pattern of such a horn radiator becomes identical in all planes, i.e. circularly symmetric, and has in theory no inherent cross-polarization components. In practice, the maxima of cross-polarization can be reduced typically to values between −30 and −40 dB, compared to −18 dB for a smooth horn (relative to the maximum of co-polarization), resulting in relative bandwidths of up to an octave (**Fig. 3**). At present the corrugated horn is the best technical solution for a wideband radiator with two orthogonal planes or polarization. The only



E Ellipsoid
F Focal point
H Hyperbola
P Parabola

Fig. 1 Examples of possible reflector combinations

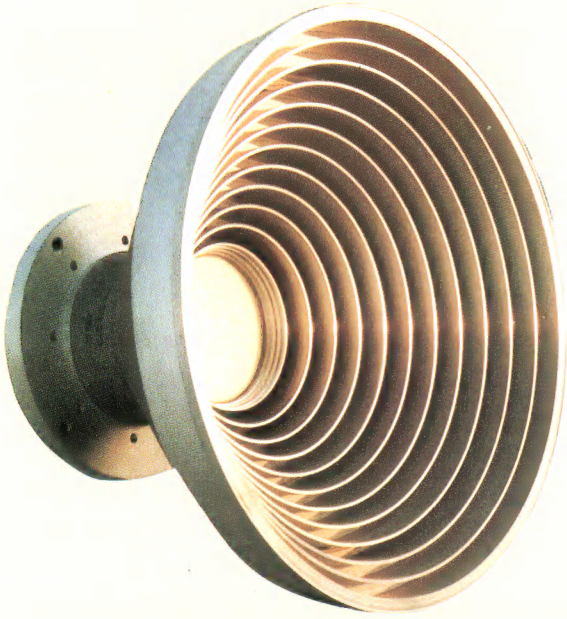


Fig. 2 Corrugated horn radiator; this antenna type reduces inherent cross-polarization components to values between −30 and −40 dB

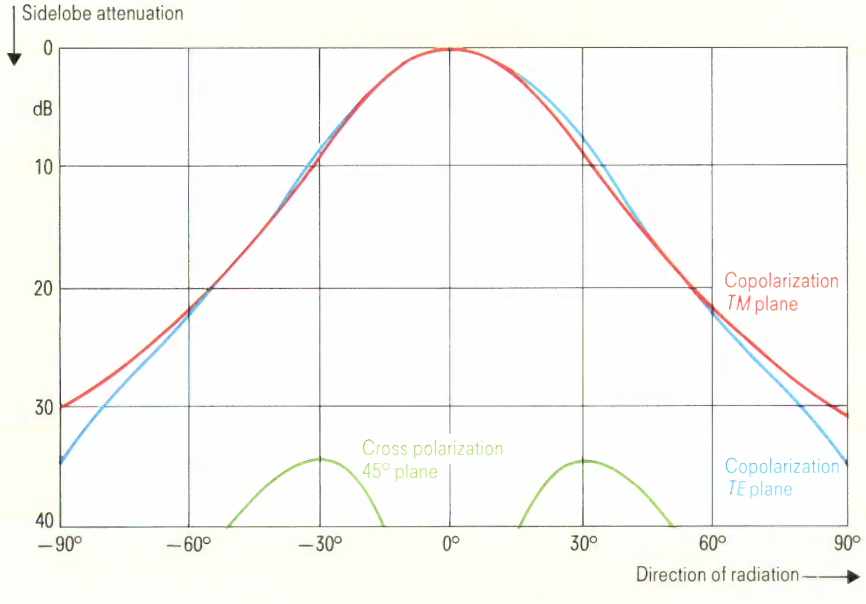


Fig. 3 Typical far-field radiation patterns of a corrugated horn radiator

disadvantages are increased production costs and a slightly increased weight. On the other hand, the generation and superposition of discrete higher-order modes for achieving field symmetry have technical consequences of lesser importance.

Improving the sidelobe attenuation

Depending upon the design, the sidelobe distribution of an aperture antenna is determined mainly by the aperture field attained, by the spillover from the feed elements as well as by the type and size of obstructing elements in the aperture. Unobstructed apertures with suitably optimized field distribution yield favorable radiation characteristics. This has led to the development of so-called *offset antennas* with a laterally offset feed. Shell-type antennas are representative of this design in radio relay systems. In contrast, parabolic-reflector antennas with partially obstructed apertures have radiation patterns with substantially higher sidelobes. The spillover is reduced and can easily be controlled when corrugated horn feeds are used, although this has a substantial effect on the radiation pattern only in the case of parabolic-reflector antennas. A reduction of the sidelobes can be achieved on all types of antennas when the illumination is reduced towards the rim of the reflector, but a corresponding reduction in antenna gain must be accepted.

Additional measures which have an effect at larger off-axis angles of the radiation pattern are, for example, the fitting of suitable edge blinders. An example of the achievable effect is shown in **Fig. 4** for a 3 m parabolic antenna for the 2 GHz band. For further improvement in the radiation pattern with standard parabolic antennas a planar radome is most frequently used. It consists of a cylindrical shroud, coated inside with RF absorbing material and covered with a low-loss dielectric window, which simultaneously offers climatic protection for the feed. Corresponding measures in the case of shell-type antennas are extending the housing walls further forward and additionally coating them on the weather-protected inner surface with RF absorbing material.

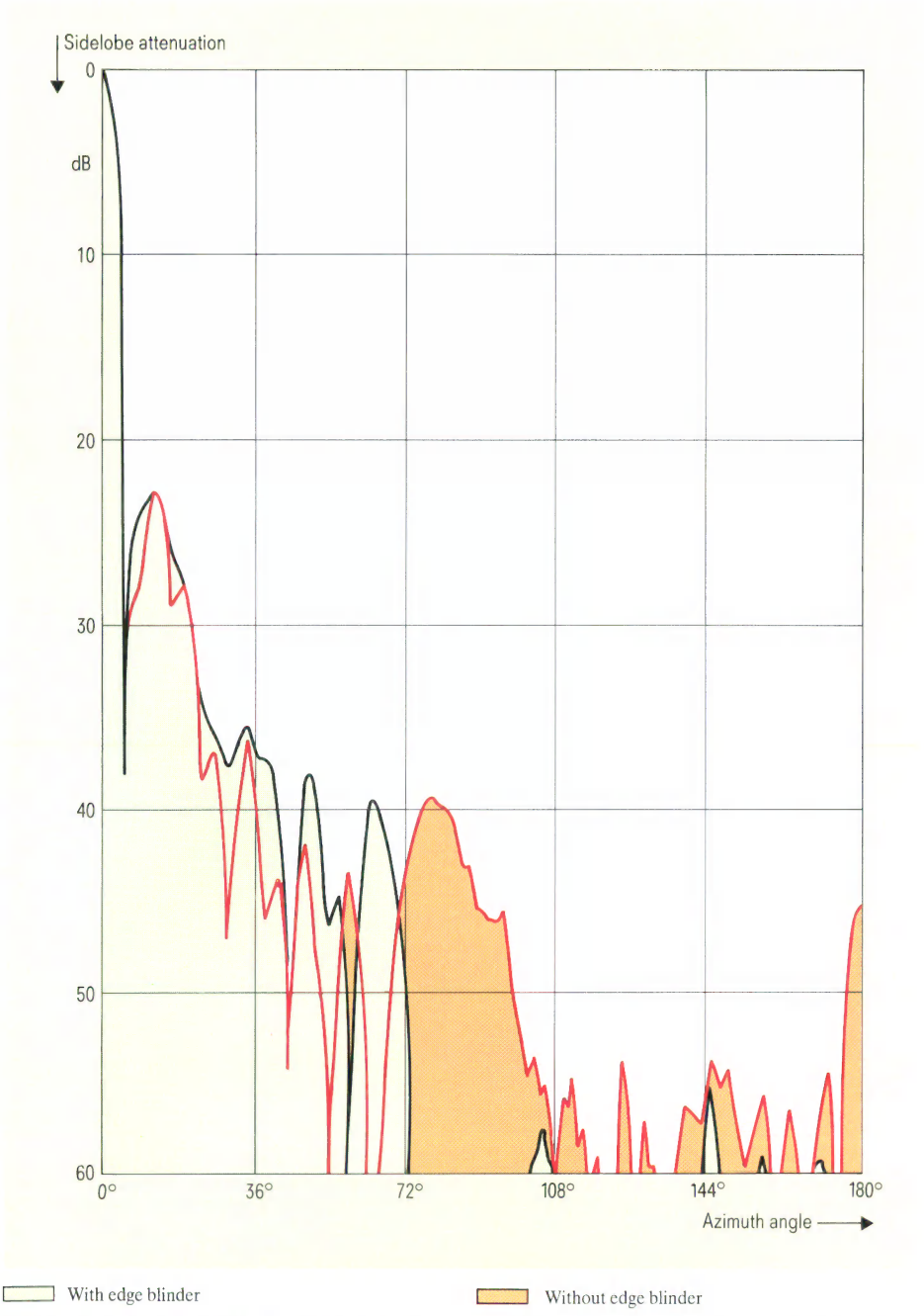


Fig. 4 The effect of edge blinders on the radiation pattern of a vertically polarized 3-m parabolic antenna ($f = 1.7$ GHz)

Improving the cross-polarization characteristics

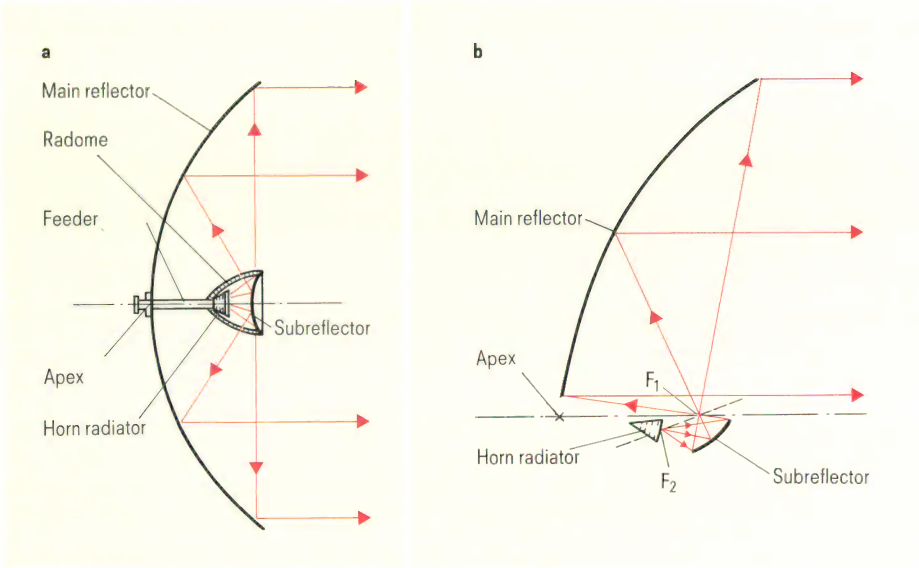
Simultaneous transmission of two orthogonal linearly polarized signals (e.g. in horizontal and vertical planes of polarization) of the same frequency without mutual interference on the same path makes substantially greater communication capacity available. Such cochannel operation is also referred to as *"frequency reuse"*; it requires antennas with *cross-polarization discrimination* of about 30 to 35 dB, i.e. suppression of the interfering component orthogonal to the required polarization. Cross-polarization contributions of an antenna are attributable to various physical causes [1].

One contribution arises from the polarization diplexer directly connected to the primary radiator. This diplexer is usually provided with two waveguide or coaxial input ports associated with the signal lines, and these produce two linear orthogonal polarizations in the connected circular or square waveguides. The achievable discrimination depends on the purity of the polarization produced by the coupling mechanism, and how well the mechanical symmetry of the design as well as the suppression of interfering higher-order modes can be realized. Typical values for the discrimination are at least 45 to 50 dB, i.e. sufficiently below the values specified for the whole antenna.

When a parabolic reflector is illuminated by a circularly symmetric primary field free from cross-polarization, the curvature of the reflector produces only small cross-polarization components. Their maxima lie typically at about −50 dB relative to the main lobe maximum of the co-polarization. No cross-polarization occurs in the two planes of reflector symmetry which are determined by the plane of linear polarization and the orthogonal plane; appropriately, the four maxima are found in the 45° planes.

If the primary field itself is not ideally symmetrical and includes cross-polarization components, the spatial radiation pattern of the antenna will exhibit a corresponding increase in the cross-polarization maxima. When customary corrugated horns are used, this means that the contribution from the reflector is generally negligible because that from the primary radiator usually predominates. In radio relay applications, the particularly important azimuth radiation pattern of the antenna, i.e. the horizontal distribution of radiation, is only slightly impaired by the cross-polarization maxima in the 45° planes. Maximum symmetry in the primary radiator design and its mounting on the antenna are of prime importance, and this can easily be achieved with Cassegrain arrangements, for example (**Fig. 5a**).

Reflectors with an offset feed, such as shell-type antennas, have only one line of symmetry. When illuminated directly from the focal point, their far-field radiation patterns exhibit pronounced cross-polarization maxima on each side of the direction of maximum radiation. They are situated in a plane perpendicular to the line of symmetry, i.e. they are directly associated with the azimuth radiation pattern. A substantial improvement can be achieved by combining the asymmetric main reflector with a suitably shaped secondary reflector in such manner that the polarization distortions generated by the two reflec-



F_1 Focal point of paraboloid F_1, F_2 Focal points of ellipse

Fig. 5 Basic structure of the symmetrical Cassegrain antenna (a) and the Gregorian shell-type antenna (b)

tors just cancel each other. Such systems, the theory of which cannot be dealt with here, are employed in shell-type antennas (**Fig. 5b**). In practice, this method can reduce the magnitude of the cross-polarization maxima in the azimuth plane from about −17 dB for a normal design with a direct feed to about −30 to −35 dB for a double-reflector antenna. This method exhibits wideband properties [2].

Multiband use of antennas

The advantages of operating radio relay antennas simultaneously in two separate frequency bands have been discussed for some time and used in some setups. The objective is to achieve the same transmission capacity using only *one* antenna as that for which two antennas were previously required. In addition to other savings, this is of particular interest in view of the shortage of mounting space on radio relay towers. An optimum combination has become possible recently through the production of wideband system combining networks, i.e. complex waveguide networks for combining different signal paths, using new principles and manufacturing methods [3], as well as through extensive development work aimed at the production of suitable wideband primary radiators in the form of optimized corrugated horns. Such feed systems are used for shell-type antennas and have produced very good electrical properties.

Shell-type antennas

The advantages of asymmetric parabolic antennas in general and of the subgroup shell-type antennas in particular, namely their excellent radiation patterns and their favorable reflection properties, make them particularly suitable for use in the majority of cases. This argument weighs even more, since they fully meet the more stringent requirements of modern radio relay networks, which can hardly be achieved with other antenna designs.

A new design for such antennas has been produced in order to meet the variety of requirements for both the mechanical and electrical properties and the fields of application. This is illustrated in **Fig. 6**.

Mechanical design

The mechanical reference plane and the load bearing element are formed by a rigid base frame of angle iron, on which a highly accurate paraboloidal reflector segment of light-weight aluminum construction is mounted in a vibration-free manner. The prefabricated shell-type housing is mounted around this structural unit and provides the reflector with complete protection against wind and weather – the whole antenna can withstand wind loads up to a maximum of 210 km/h. The base frame is prepared for the accurate mounting of a great variety of radiator assemblies; for example, the supports for radiators incorporating an additional subreflector are accurately located by means of alignment pins and then fixed with screws.

Struts connect the base frame to a ring-shaped mounting frame of steel; the mounting frame and the antenna body are transported separately. The clamps for holding the antenna to the platform

Fig. 6 Fabrication of a 3-m shell-type antenna (courtesy of Zarges Co.)

are attached to the mounting frame in four clamping zones. Horizontal friction bearings and a vertical threaded shaft permit adjustment of the antenna by ±5° in azimuth and ±3° in elevation. Enough space is left between the structs and the adjusting elements so that even double-reflector systems and dual-band radiators with system combining networks may be attached. The antenna can easily be modified for a different frequency band by exchanging the relevant radiator assemblies.

The internal walls of the housing – the internal space is accessible for installation purposes through a manhole – are coated with RF absorber material. A suitable dielectric window provides a weatherproof covering for the antenna aperture.

The high mechanical accuracy and the rigid torsion and vibration resistant construction make the antenna universally suitable for all frequency bands between about 2 GHz and 13 GHz.

Design variants

The antenna may be further improved in respect of its sidelobe attenuation, particularly in the 2 GHz band, by an additional optional projecting structure. Furthermore, a variant with reduced height, i.e. a slightly reduced gain, is available for use with particularly small platform spacings.

Electrical characteristics

Several radiator assemblies for various frequency bands are available. The most important electrical data of typical modern shell-type antennas are listed in **Table 1**. Apart from the more recent development mentioned in this article, a multitude of design variants of the proven versions for nearly all radio relay frequency ranges and applications specified by CCIR are available, and this applies equally to the parabolic-reflector antennas described below.

The potential of the new concept will be further illustrated, using the 2.2/3.5 GHz shell-type antenna with wideband corrugated horn radiator including a system combining network, as well as the 3.9 GHz shell-type antenna with corrugated horn radiator and subreflector as examples. **Fig. 7** shows for the shell-type antenna the overall radiation envelopes in both planes of polarization for copolarization and for cross-polarization in the 2.2-GHz band, as well as the corresponding curves for the frequency range around 3.5 GHz. These curves show that a sidelobe attenuation of 65 dB can be achieved at angles as small as 60° (2.2 GHz) and 44° (3.5 GHz). Consequently, crossings of radio relay paths even with acute angles are admissible – a requirement which is indispensable in closely meshed networks. The excellent electrical data of the dual-band 3.9/6.7 GHz shell-type antenna with system combining network and wideband Gregorian feed system are given in **Table 1**.

An example of such an antenna installation with a 2.2/3.5 GHz system combining network and the connected antenna feeders – coaxial cable (50 Ω) for 2.2 GHz and SIRAL® waveguide S40 for 3.5 GHz – is shown in [4] (**Fig. 2** on page 6 of this special issue).

Radiator assemblies with system combining networks offer substantial advantages. Their use results in a saving of the space for an additional antenna and permits transmission of two frequency bands in each of two planes of polariza-

Type	*Frequency range* [GHz]	*Gain* [dBi/band center]	*3 dB beamwidth* [deg.]	*Sidelobe attenuation 60/65 dB from* [deg.]	*Front/back ratio* [dB]	*XPD* [dB]	*Reflection coefficient r* [%]	*Notes*
HP	2.1 to 2.3	33.4	3.8	63/74	65	32	4.5	Directly fed
SHP	2.1 to 2.3	33.4	3.8	45/72	65	32	4.5	Directly fed
HP	3.4 to 3.6	38.4	2.2	33/46	65	35	2.5	Directly fed
HP	2.1 to 2.3/	33.8/	3.5/	60/60	65	35	4.5	Directly fed
	3.4 to 3.6	38.1	2.2	6/44	65	35	4.0	with system combiner
HP	3.4 to 4.2	38.9	2.0	39/45	65	32*	3.5	Gregory subreflector
HP	3.6 to 4.2/	39.1/	1.8/	48/60	65	32*	4.5	Gregory subreflector
	6.425 to 7.125	43.2	1.1	40/60	65	32*	4.5	with system combiner

HP High performance SHP Super high performance * Over the entire azimuth range

Table 1 Typical electrical data for several shell-type antennas

Type	*Frequency range* [GHz]	*Gain* [dBi/band center]	*3 dB beamwidth* [deg.]	*Sidelobe attenuation 60/65 dB from* [deg.]	*Front/back ratio* [dB]	*XPD* [dB]	*Reflection coefficient r* [%]	*Notes*
3 m	1.7 to 2.1	32.8	3.8	84 (52 dB)/—	52	≥30	6	Directly fed with blinders
3 m	3.4 to 4.2	38.5	1.5	90 (55 dB)/—	52	≥32*	4.5	Cassegrain with blinders
3 m	6.425 to 7.125	43.6	0.8	65/80	70	≥40	3	Cassegrain with shrouded radome
3 m	10.7 to 11.7	48.5	0.7	90/95	70	≥35*	3.5	Cassegrain
0.6 m	17.7 to 19.7	39.0	1.6	90/—	60	≥37*	8.5	Cassegrain with shrouded radome

* Over entire azimuth range

Table 2 Typical electrical data for several parabolic-reflector antennas

tion with a considerable reduction in total outlay.

For this reason more of such feed systems are in preparation, e.g. for combinations of 3.9/6.2 GHz and 3.9/11.2 GHz.

The possibilities offered by these modern shell-type antennas will be further explained using a design with a subreflector, a segment of an ellipsoid of rotation, and a corrugated horn radiator for the frequency range 3.4 to 4.2 GHz as an example. The double-reflector principle results in a considerable improvement in the cross-polarization characteristics. As can be seen in **Table 1**, the minimum cross-polarization discrimination over the whole angular range in the horizontal plane important for practical application is more than 32 dB. This characteristic is specified in the systems planning of digital radio relay links. As is well known, directly-fed antennas of comparable size have a cross-polarization discrimination of only some 18 dB on both sides of the main lobe. The increased outlay for a Gregorian system is justified by the improved cross-polarization characteristics. Obviously, this principle is also suitable for multiband operation.

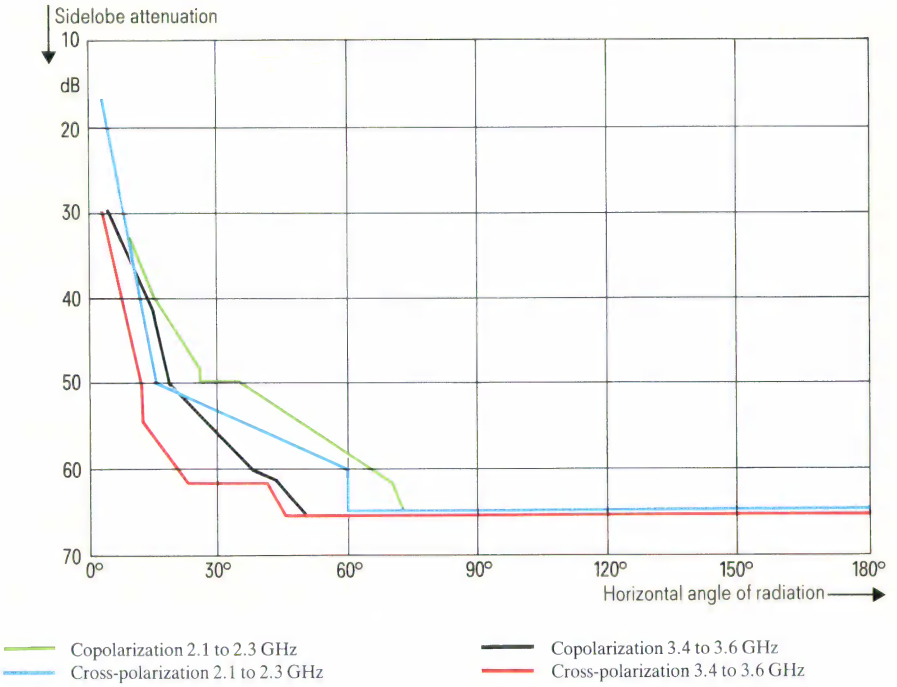


Fig. 7 Overall radiation envelope for co-polarization and cross-polarization of a 2.2/3.5 GHz shell-type antenna

Parabolic-reflector antennas

A paraboloid of rotation provides the radio relay network planner with an antenna that can be adapted to most of the transmission tasks because of the multitude of sizes, designs and types of radiator system used. Whether as shallow or deep parabolic dish, with edge blinders or cylindrical shielding shroud, cover or no cover, directly fed or via a subreflector, this basic design has retained its importance. Increased requirements placed on the characteristics and the opening up of new frequency bands have led to a continuous expansion of the available spectrum.

Five examples, representative of many new developments, will be used to demonstrate the present state of the art.

Table 2 lists the most important electrical data.

3-m parabolic antenna (Cassegrain) for 1.7 to 2.1 GHz

This antenna for two linear polarizations and with coaxial ports (50 Ω) is directly fed by a square horn radiator and is provided with edge blinders which are optimized for the frequency band for the purpose of improving the radiation pattern.

Fig. 8 3-m parabolic antenna with a shrouded radome and Cassegrain feed for the frequency band 6.425 to 7.125 GHz

3-m parabolic antenna (Cassegrain) for 3.4 to 4.2 GHz (Fig. 8)

Compliance with the specifications defined for this antenna was particularly difficult. The objective was to achieve high cross-polarization discrimination in a double-reflector system over the large bandwidth of 800 MHz with low reflection factors (cf. **Table 2**). This objective has been achieved; the sidelobe attenuation can be further improved by the use of a shrouded radome.

3-m parabolic antenna (Cassegrain) for 6.425–7.125 GHz

This antenna with a planar radome fed by a double-reflector system has outstanding cross-polarization discrimination properties, as shown in **Fig. 9**; for the other electrical data see **Table 2**.

3-m parabolic antenna (Cassegrain) for 10.7 to 11.7 GHz

The design of this antenna is also based on the Cassegrain principle (**Fig. 5**). The complete radiator assembly, comprising feeder, horn radiator, pressure window and subreflector, is inserted as a self-supporting unit from the front into the apex opening of the main reflector. Abolition of metallic struts for supporting the subreflector ensures very good cross-polarization discrimination due to the elimination of interference which could otherwise occur, and results in sidelobe maxima at azimuth angles outside the main lobe which are small for parabolic antennas.

0.6-m parabolic antenna (Cassegrain) for 17.7 to 19.7 GHz

The priority in the development of this antenna was the demand for excellent sidelobe attenuation combined with high cross-polarization discrimination. A deep parabolic dish with an integral cylindrical shroud coated inside with RF absorbing material – with a weatherproofing and low-reflection cover – is fed by a Cassegrain radiator via a short circular waveguide. **Table 2** shows the electrical data.

The examples of shell-type and parabolic antennas cited above illustrate clearly the current trend in antenna development: further improvements in radiation patterns, in particular a substantial improvement in cross-polarization discrimination, in conjunction with greater bandwidth and, in certain cases, even two frequency bands on one antenna.

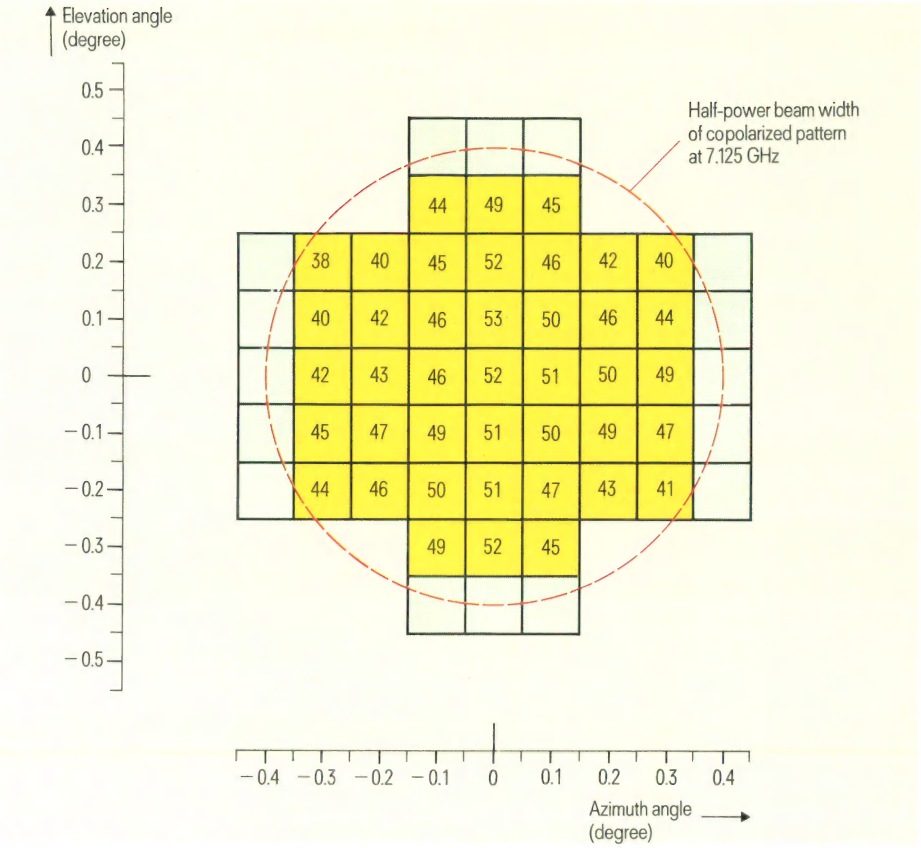


Fig. 9 Typical cross-polarization discrimination in dB around the main beam axis of a 3-m parabolic antenna with a planar radome and Cassegrain feed for the frequency band 6.425–7.125 GHz (values based on main beam maximum)

Antenna feeders

Coaxial cables with a corrugated outer conductor and a smooth or corrugated inner conductor have proved a success worldwide in the frequency range below 3 GHz. Waveguides of various cross sections are preferred at higher frequencies because of their more favorable losses. Recently, SIRAL waveguide (developed in several standard rectangular internal cross sections) has gained particular importance because it can be bent and twisted on site without loosing its wideband low-reflection characteristics. The development of appropriate transitions and mode filter has made it possible for SIRAL waveguide to be used in an overmoded version. The losses are very much lower than in the fundamental mode [5, 6]. Further very advantageous applications are found in the simultaneous transmission of several radio relay frequency bands simultaneously through one SIRAL waveguide, e.g. 4/11 and 11/14 GHz. In this multiple frequency band operation the lower frequencies are transmitted in the fundamental mode, and the higher frequencies in the overmoded operation mode.

SIRAL waveguide has been employed successfully at 11/14 GHz (ECS earth station), 12 GHz (AM-TV distribution system), as well as at 13 and 15 GHz (digital radio relay). Other advantages typical of SIRAL, such as the possibility of accurate alignment in installation and adaptation to the local installation inaccuracies, are fully retained.

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Low-loss Feeder for Radio Relay and Radar Systems

Valuable energy is lost due to the attenuation in feeders between radio equipments and antennas. For this reason, waveguides operating in their single-mode range are used at frequencies above 3 GHz.

SIRAL® waveguides can now be used above their single-mode range when a special simple mode filter is employed. This provides a substantial reduction in losses when compared with other waveguides operating in their single-mode range. For example, the feeder loss in the frequency range between 10 and 15.4 GHz is reduced to less than one third of the original dB value by using this "low-loss SIRAL waveguide." Even better loss figures can be achieved in other frequency ranges.

SIRAL waveguides have been used for many years in radio relay stations. Because they are a special rectangular type which can be bent and twisted and supplied on drums or in crates, they can therefore be easily installed [1, 2]. Their cross sections, which conform to rectangular waveguide standards, cover the entire frequency range from 3.2 to 18.0 GHz when they are operated in the usual manner below their single-mode limit. Their low reflection coefficients, linearity at joints, approximately 9% lower loss in comparison with rigid rectangular aluminum waveguides and, not least their ease of installation in long sections have contributed to their excellent record as feeders in radio relay, radar and satellite systems.

Using SIRAL waveguides at higher frequencies – above their single-mode limits – offers a further reduction in losses by about two thirds to three quarters when additional waveguide components, i.e. waveguide transitions and mode filters, are employed.

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Low-loss "overmoded" waveguides

Method of operation

Energy of a certain frequency range can be propagated in any waveguide in only one electromagnetic field pattern, the fundamental mode, depending on the geometric cross-sectional dimensions. Above a certain frequency – the single-mode limit – a further mode can be propagated and thus the lower cutoff frequency of this first higher-order mode is the single-mode limit. The type of higher-order mode which can be propagated in a given waveguide at any frequency is known, since each of the infinite number of modes has its own lower cutoff frequency. However, each of the modes has its own propagation velocity. Consequently, a modulated RF signal transmitted by several modes is subject to different transmission delays through the waveguide and echoes are produced. This is considered in greater detail in [3].

For perfect transmission of modulated RF signals, care must be taken to ensure that the smallest possible number of higher-order modes is produced, or that those unavoidably generated at

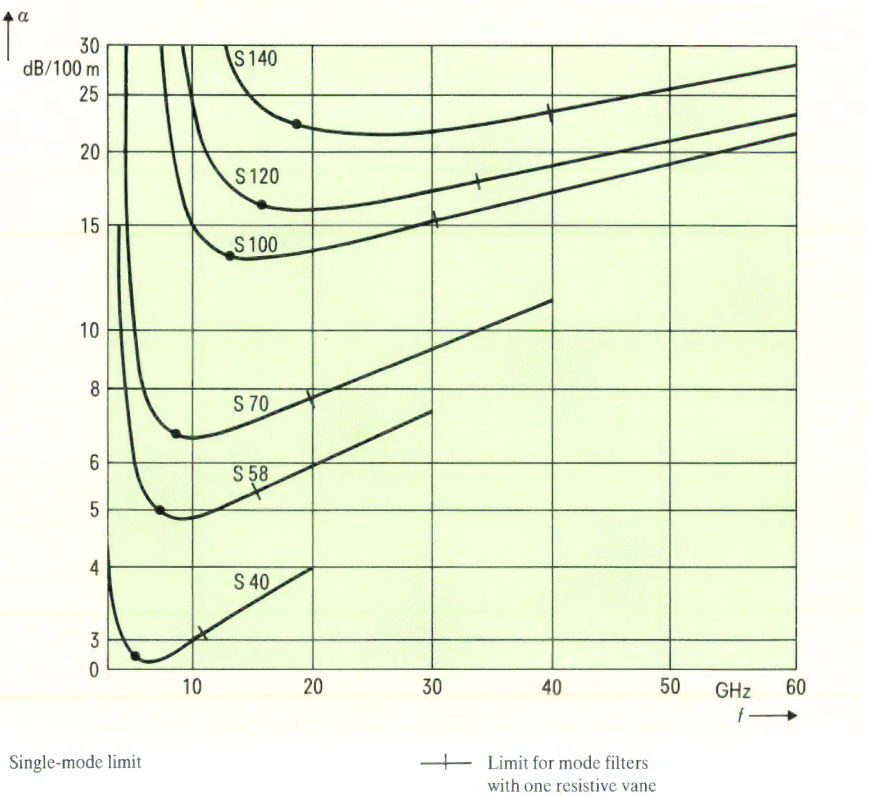


Fig. 1 Frequency response of losses in SIRAL waveguides

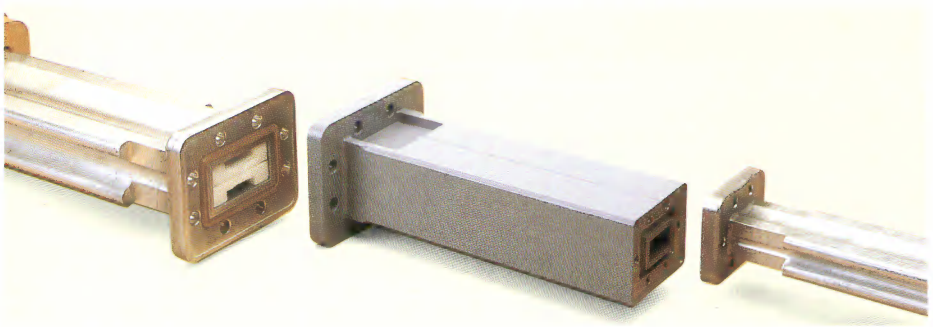
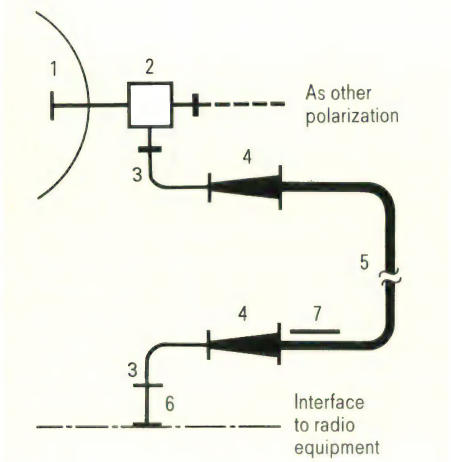


Fig. 2 Waveguide transition from S 58 to S 120 with a mode filter inserted in the S 58 waveguide

inhomogeneities (e.g. bends, twists, flange offsets or cross-section changes) are substantially attenuated. This can be achieved by means of mode filters.

Now that the problem of using SIRAL waveguides for transmitting modulated signals above the single-mode limit has been solved, it is possible to manufacture feeders with substantially lower losses. For example, the loss in an 11-GHz system employing the single-mode SIRAL waveguide, S 100, as antenna feeder is about 14 dB/100 m. This figure is reduced to about 3 dB/100 m when the new feeder system incorporating S 40 SIRAL waveguide, with a mode filter is employed.

Fig. 1 shows the losses as a function of frequency for all SIRAL waveguides which can be used for low-loss applications.



1 Antenna
2 Polarization diplexer or transition for one polarization
3 SIRAL S 120 (only for short sections)
4 Transition from PDR 120 to PDR 58
5 SIRAL S 58
6 Pressurizing section PDR 120
7 Mode filter

Fig. 3 Schematic layout of a radio relay antenna system for the 15-GHz band using low-loss SIRAL waveguide, S 58 d

Waveguides operated above their single-mode limit will hereafter be referred to as "overmoded waveguides," in accordance with Anglo-American usage. The waveguide designation (e.g. S 40) will contain the suffix "d."

Design

The design of an "overmoded" feeder will be discussed with reference to digital radio relay systems in the 13-GHz and 15-GHz bands (12.75 to 13.25 GHz and 14.50 to 15.35 GHz).

SIRAL S 58 waveguide is connected by means of waveguide transitions (PDR 120 to PDR 58) to the feeder ports PDR 120, of equipments and antennas operating under single-mode conditions, and a mode filter is inserted. **Fig. 2** shows the feeder combination, S 58 d, comprising SIRAL waveguides, S 120 and S 58, with a mode filter and a waveguide transition inserted. In addition to the fundamental mode, eleven higher-order modes in the upper frequency range can propagate in the cross section of the S 58. Five of these modes can be excited. They are adequately attenuated by the mode filter shown. **Fig. 3** shows schematically the "overmoded" feeder arrangement.

Waveguide transition and mode filter

The waveguide transition was specially developed for applications of this technique and its mechanical features have been adapted to suit SIRAL waveguides. The transition consists of two aluminum half-shells which are soldered together after the waveguide profile has been milled. The transition can be matched by means of adjustment screws to a reflection coefficient of less than 1.5% over the relevant frequency band.

The mode filter comprises one or several resin-bonded paper vanes with dove-tail ends and a vapor-deposited resistive layer. The vanes are located in the waveguide parallel to the broad wall by means of hard expanded plastic. **Fig. 4** shows a mode filter with one resistive vane as used in the above design example. Filters with three or more resistive vanes are required for applications in other frequency bands.

The insertion loss of the filter is less than 0.3 dB per resistive vane at the fundamental mode and the reflection coefficient is less than 1%.

Electrical properties

Tests to confirm by measurement the calculated electrical properties have been performed on the design example shown in **Fig. 3**.

Three type S 58 d low-loss feeders with lengths of 5, 14 and 32 m were compared with corresponding lengths of SIRAL S 120 feeder. **Fig. 5** shows that the loss was reduced by two thirds compared with the S 120 feeder. Only small residual contributions from higher-

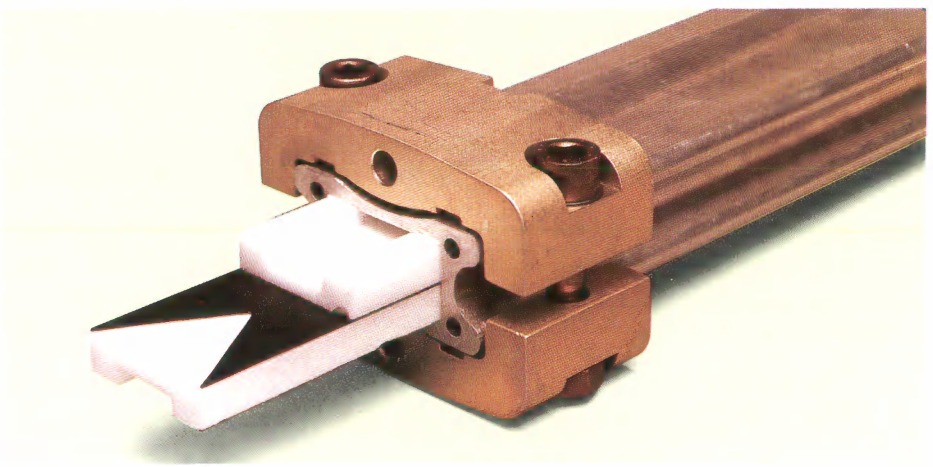


Fig. 4 Cut-away view of the mode filter, partially inserted into the waveguide

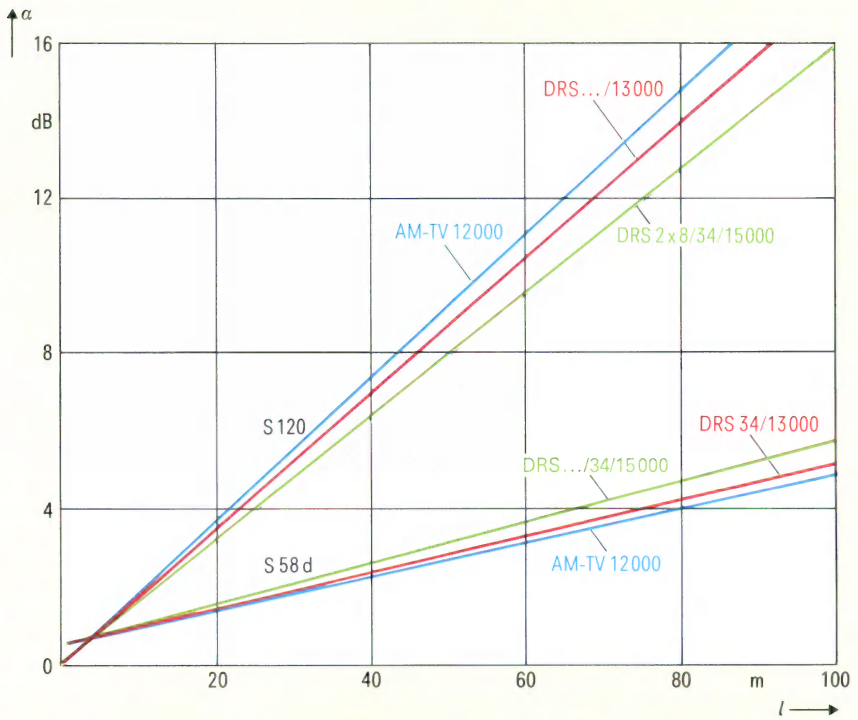


Fig. 5 Comparison of losses in SIRAL waveguide, S 120, and a low-loss "overmoded" waveguide, S 56 d, as a function of line length in systems with different frequency ranges

order modes can be detected when a mode filter is used in each feeder. The attenuation response of the feeders has superimposed on it loss fluctuations of only 0.1 to 0.2 dB in the case of a 14-m feeder, for example, and these fluctuations diminish with increasing length.

Tests carried out on a 14 m long S 58 d test feeder employed in digital radio relay systems, DRS 2×8/15000, revealed no increase in bit error ratio as compared with a SIRAL S 120 feeder of identical length [3, 4].

Limits for "overmoded" feeders

Maximum operating frequency

The loss-reducing design of the SIRAL feeder using an "overmoded" waveguide with two transitions and a mode filter comprising one resistive vane, has a cutoff frequency. Above this frequency the propagation of a higher order mode is possible which cannot be suppressed by this mode filter. The cutoff frequency for this mode is the upper limit for the applicability of the "overmoded" waveguide. When a mode filter with three resistive vanes is used, this limit can be raised to about 1.5 times this figure. A similar mode filter with five resistive vanes for the next higher-order mode will raise the frequency limit to approximately twice that value. Although it is possible to increase the number of resistive vanes still further, this is inadvisable, because each of the vanes also slightly increases the loss at the fundamental mode.

The use of this new type of feeder is not limited to S 58 waveguide, but extends to all existing SIRAL cross sections. Consequently, **Table 1** lists for SIRAL waveguides, S 40 to S 140, the cutoff frequencies of mode filters comprising one, three and five resistive vanes.

Table 2 lists a number of low-loss waveguide combinations for "overmoded"

SIRAL waveguide	Frequency limits f_c in GHz for mode filters with		
	1 vane	3 vanes	5 vanes
S 40	10.72	15.82	20.89
S 58	15.48	22.84	30.28
S 70	19.75	29.33	38.91
S 100	30.84	45.66	60.60
S 120	33.19	48.99	64.94
S 140	39.84	59.17	78.44

Table 1 Upper frequency limits (f_c) for low-loss SIRAL waveguide when different mode filters are used

feeders using a mode filter with one resistive vane. The loss for the single-mode and "overmoded" waveguides is given for the appropriate operating frequency range. **Fig. 1** also shows that the waveguide loss diminishes with increasing frequency in the single-mode range. However, the loss generally increases with frequency in the "overmoded" range.

If a mode-filter with three or five resistive vanes is used, then many more waveguide combinations, some providing a substantial improvement in the loss characteristics, are possible.

Minimum feeder length

As mentioned above, the small loss peaks superimposed on the attenuation response of the feeder amount to some 0.1 dB in the above design example with a feeder length of 14 m, falling in inverse proportion to the length. Consequently, the shortest feeder length is determined by the maximum permissible loss peaks.

Further determining factors for the shortest practical feeder length are the size of any profitable loss reduction and the internal losses in the mode filter.

Feeder combination		*Frequency range in GHz*		*Attenuation in dB/100 m*			
Low-loss waveguide	Single-mode waveguide			Low-loss waveguide		Single-mode waveguide	
		from	to	from	to	from	to
S 40	S 70	5.4	10.7	2.8	3.1	10.0	6.7
S 58	S 100	8.2	12.4	4.9	5.1	19.9	13.6
S 58	S 120	10.0	15.4	4.9	5.4	24.0	16.4
S 58	S 140	12.4	15.4	5.1	5.4	30.9	24.2
S 70	S 120	10.0	15.8	6.7	7.2	24.0	16.3
S 70	S 140	12.4	18.0	6.8	7.5	30.9	22.4

Table 2 Frequency range for various SIRAL waveguide combinations in accordance with the low-loss feeder arrangement described

Possible applications for "overmoded" feeders

The new low-loss feeder system described above has so far been used for transmit and receive feeders in earth stations of the ECS 11/14 satellite system, in the AM-TV distribution system in the 12-GHz band and in digital radio relay systems for 13 GHz and 15 GHz. Furthermore, the "overmoded" SIRAL S 70 d waveguide in conjunction with R 220 waveguide in the digital radio relay systems, DRS 8, DRS 34 and DRS 140 for the 18-GHz band (17.9 to 19.9 GHz) has been installed in many projects. Here, the loss of about 60 dB/100 m can be reduced to less than 8 dB/100 m. A reduction in feeder losses is also a significant advantage for radar systems in the 10 and 16 GHz bands.

A further application of "overmoded" SIRAL waveguides could be envisioned in frequency-modulated systems, such as narrowband FDM systems or TV systems, provided the noise figures are not adversely affected. By employing a mode filter with three resistive vanes, SIRAL S 40 waveguide could also be used as an "overmoded" S 40 d feeder in conjunction with S 100 waveguide in the 11-GHz band. In this case, the feeder loss would be reduced by more than 10 dB/100 m to about 3 dB/100 m.

This further development of SIRAL waveguides enables not only single-mode feeders for 3.2 to 18 GHz to be realized, but also low-loss "overmoded" SIRAL feeders for the entire frequency range from 5.4 to 78.4 GHz.

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Channel Branching Filters for Wideband Radio Relay Systems

In radio relay systems, several transmitters and receivers are usually operated on a single common antenna. Channel branching filter chains are used to combine the various signal paths in the transmit section without mutual interference and to separate them again in the receive section. In modern radio relay transmission systems, they invariably consist of multiple-resonator band-pass filters interconnected via circulators.

After a brief discussion of the physical factors relating to filters and circulators insofar as they are important for channel branching filter design, the electrical and mechanical design of modern channel branching filters are described giving particular consideration to the fabrication methods used. Test results are given for channel branching filters employed in the DRS 140/6700 digital radio relay system.

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Basic channel branching filter design

Fig. 1 shows schematically the path of a signal through the channel branching filter chain of a radio relay system from transmitter to antenna, and the return path from antenna to receiver (see [1] for a more detailed description). The transmit and receive sections in this arrangement are mutually isolated by means of a circulator.

Normally, the orthogonally polarized channel groups (groups 1, 3, 5, 7 and 2, 4, 6, 8 in **Fig. 1**) are mutually displaced in frequency by one half of the channel branching filter spacing in order to achieve adequate adjacent channel discrimination (interleaved pattern). In digital systems, the orthogonally polarized channel groups can, however, also be operated on the same radio frequencies (cochannel pattern), thereby improving bandwidth utilization.

A polarization diplexer brings together the two orthogonally polarized channel groups. When the diplexer is designed as a system branching network, the RF channels of another radio relay frequency band can be fed to the same antenna [2].

Band-pass filter

Loss analysis

The losses in a channel branching filter are mainly determined by the *band-pass filter*. This is due to the fact that, because of the width of the RF signal spectrum and the high carrier frequency, the relative filter bandwidths are only in the order of 1%. As the losses are known to be in inverse proportion to the product of the relative pass band and the Q factor of a band-pass filter, the latter value must be as high as possible to

ensure that system quality is not impaired.

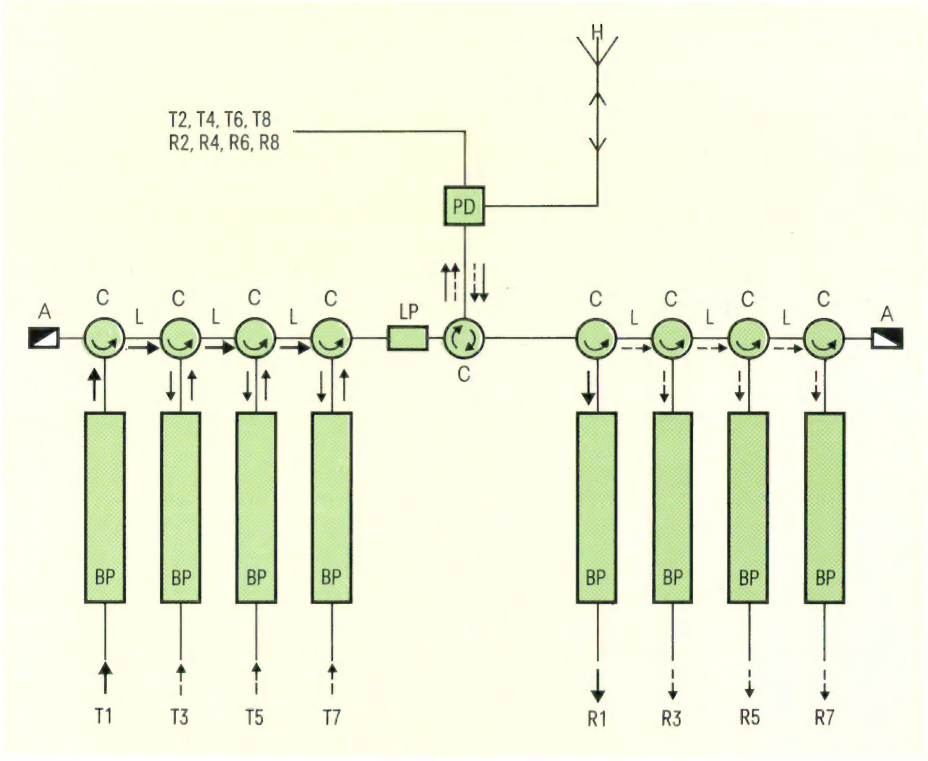
Transmission line resonators are mostly used at microwave frequencies, since, in addition to the dielectric loss angle, the *current density* is the determining factor for the losses. The planar stripline arrangements frequently used elsewhere are unsuitable for channel branching filters because of their unfavorable current density distribution. On the other hand, the current density in coaxial line or waveguide resonators becomes smaller as the volume increases.

The Q factor of resonators of this kind is known to increase with the square root of the frequency (skin effect); this applies to a constant line cross section and therefore to a volume decreasing with the wavelength. Thus, for a given volume, the Q will therefore increase proportionally to frequency, because of the proportionality between the Q and the square root of the line cross section. Assuming an approximately equal bandwidth of the RF signal spectrum in the ranges of interest and, consequently, a relative filter bandwidth inversely proportional to the carrier frequency, it follows that the losses in the band-pass filters become, to a first approximation, independent of the frequency. Accordingly, an approximately equal volume should be selected for channel branching filters at different frequencies – an advantageous solution in terms of physical design.

In accordance with these basic considerations, coaxial resonators are mainly used below about 5 GHz and cavity resonators are used above this frequency. At considerably higher frequencies, the desirable resonator volume can only be achieved by utilizing higher-order waveguide modes. Then, however, the requirement to eliminate spurious modes demands costly design measures which also cancel out some of the "gain in Q." Consequently, at such high frequencies an increase in losses is accepted in most cases.

Filter design

The small relative bandwidth of the bandpass filters permits low-pass prototype synthesis, with subsequent transformation to band-pass. In most cases, the attenuation skirts have to be made steeper using poles, so that selectivity requirements can be met.



A	Absorber	LP	Low-pass filter
BP	Band-pass filter	PD	Polarization diplexer
C	Circulator	R	Receiver
H	Radio hop	T	Transmitter
L	Coaxial line		

Fig. 1 Schematic diagram of the channel branching filters for a radio relay hop

At microwave frequencies, these attenuation poles cannot be implemented as circuit elements – unlike at lower frequencies where the networks can be designed from lumped reactances. For this reason, the poles are produced with the aid of interference cancellation by connecting non-consecutive resonant circuits in the signal path (bypasses).

Fig. 2 shows a 6th order low-pass network and the same network transformed into a band-pass. The LC resonant circuits are symbols for any form of resonator. Impedance inverters are inserted between the resonators to act as coupling circuits. The inverter constants are determined by the low-pass network elements and the required bandwidth [3]. Additional coupling elements are required in order to provide the above bypasses. For example, in the arrangement shown in **Fig. 2** they connect the first and the sixth and the second and fifth resonant circuit. For this reason, the resonant circuits must be geometrically adjacent to each other, which is made possible by arranging the resonators in a U-shaped formation. **Fig. 3** shows the attenuation characteristic of a six-section channel branching band-pass filter for the DRS 140/6700 system with only one coupling bridge.

Mechanical design and method of manufacture

Band-pass filters must meet the design specifications within close tolerances – particularly in respect of delay distortion – over the entire range of climatic conditions. Consequently, particular emphasis must be placed on minimizing temperature sensitivity.

Fig. 4 illustrates the mechanical design of a channel branching band-pass filter. A rectangular external shape has been selected for the waveguide and coaxial resonators for reasons of economy. Thus, plates or sheet metal can be used for constructing the filters. Due to the extremely stringent specifications with respect to the effect of temperature changes on their dimensional stability, these filters are manufactured from a special steel (VACODIL® 36) with

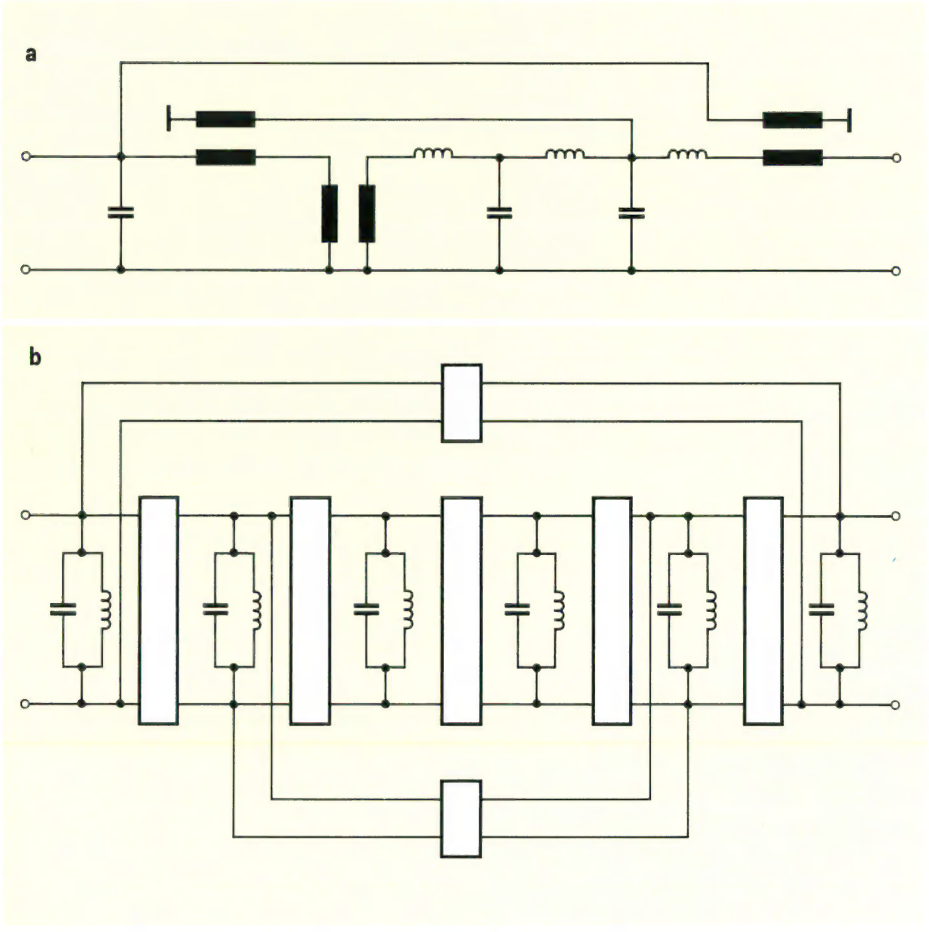


Fig. 2 Example of a low-pass circuit (a) obtained by synthesis, and the band-pass circuit with impedance inverters (b) obtained by transformation from the former

extremely small thermal linear expansion. This product is manufactured by the Siemens subsidiary, *Vacuumschmelze GmbH* of Hanau in the Federal Republic of Germany. A wall thickness of 4 mm has been chosen so that tuning screws for the resonator coupling can be accommodated in the partition. Sheets of this thickness can be processed economically and with sufficient accuracy by means of a precision punching method.

The filter cavities must be silver-plated to reduce losses. Since the coupling apertures are too small for internal silver-plating of fully assembled resonators, this plating must be applied in advance. A two-stage soldering method has proved effective – instead of the screwed connections mainly used previously. In this process, the components are first connected together by spot-welding in a jig to form a frame and then brazed in a continuous furnace. When these operations have been completed, the frame is silver-plated, and then, in a second soldering process at a lower temperature, the frame is closed with two lids which have already been silver-plated. A threaded bush for each resonant circuit is soldered into one of the lids to receive the elements for frequency adjustment.

Metal rods are used as tuning elements in coaxial resonators, but rods of dielectric material are used in cavity resonators. The lengths and materials used for the tuning elements are chosen such that the variation in the center frequency over the specified temperature range will not exceed the permissible limits (temperature coefficient less than $3 \cdot 10^{-6}$/°C). The threaded bushes for the tuning rods are axially tensioned by spring-loading to provide the required freedom from backlash. The tuning rods are secured against rotation by axially tensioning the bushes after the tuning process.

To connect the filters and adjacent microwave components (e.g. circulators), the input and output ports are designed as coaxial flange connectors, irrespective of the type of resonator used.

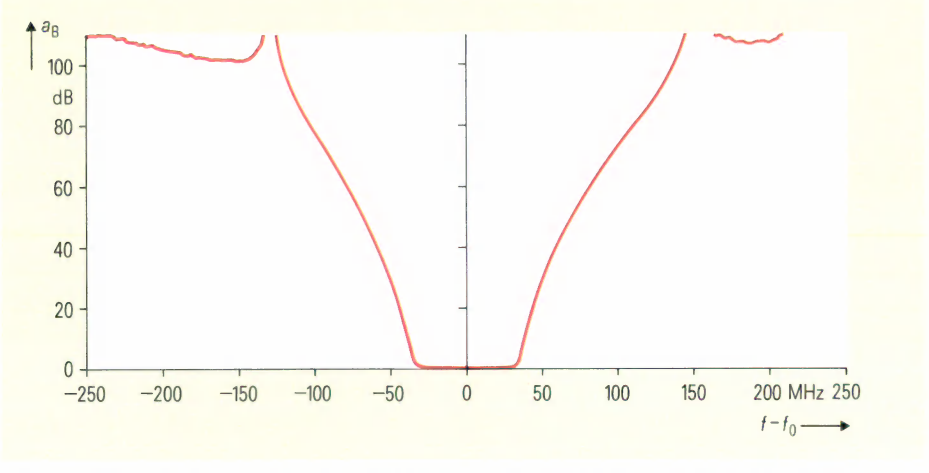


Fig. 3 Loss a_B of a six-section channel branching band-pass filter for the digital radio relay system, DRS 140/6700, as a function of frequency f ($a_o = 0.8$ dB; $\Delta f_{3\,dB} = 70$ MHz)

Filter tuning

The 3-dB bandwidth must be closely adhered to, as it determines the delay distortion in the pass band of the channel branching band-pass filter. The coupling factors must be set accurately to the nominal values for each channel frequency because of the unavoidable frequency dependence of the aperture coupling. This, as well as precise tuning of the frequencies of the individual resonators, requires a computer-controlled test setup which issues qualitatively and quantitatively accurate instructions for the tuning steps to be carried out and checks the result. This method has substantially reduced tuning complexity in comparison with earlier methods.

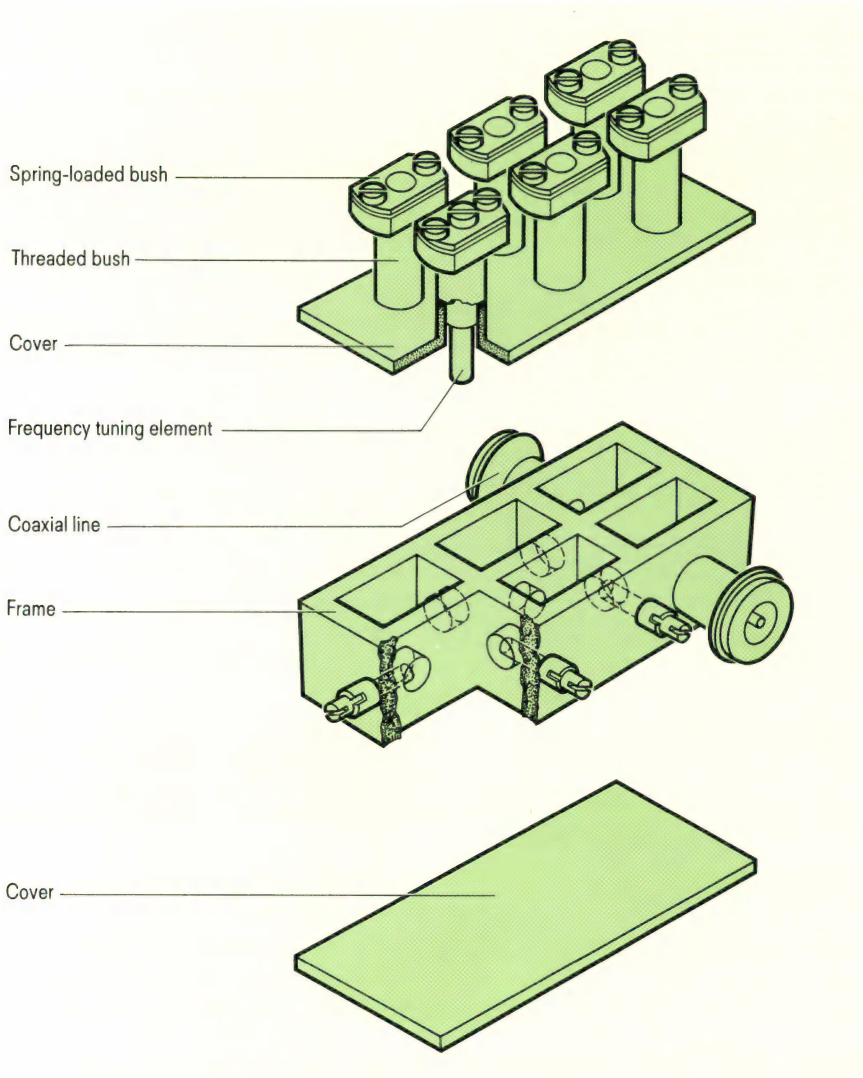


Fig. 4 Assembly of a six-section band-pass filter comprising cavity resonators with bypasses

Circulators

Materials and designs

Circulators are nonreciprocal branching devices with three (or occasionally four or five) ports. Basically, an RF signal fed into one of the ports is transmitted only to the next adjacent port in a particular direction of rotation. The circulator inhibits signal flow to each of the other ports. Loss-free transmission, complete isolation and the resultant perfect match which would be achieved by an ideal circulator are naturally impossible in practice. Consequently, a circulator is mainly judged on its loss performance and the degree of isolation provided between input and output ports.

It is well known that these unidirectional transmission properties depend on the interaction between an RF field and non-compensated spin moments in ferrimagnetic materials – the so-called ferrites. Furthermore, the extremely low electrical conductivity of these materials is important for microwave applications because an interaction with the spin moments is only possible due to the resultant deep penetration by the RF field. Of the various types of ferrite, the yttrium garnets have proved to be particularly suitable for circulators at frequencies up to 6 GHz and spinel ferrites at frequencies above 6 GHz.

Although various circulator designs are possible, modern microwave transmission systems generally only employ *Y-junction circulators*. They can be designed for use in *rectangular waveguides*, in *striplines*, and – in particularly compact form – in *microstrip lines*. All junction circulators have one or two premagnetized ferrite disks in the center of a 3-way line junction with adjacent ports forming an angle of 120° (**Fig. 5**).

While *microstrip* circulators do not meet the stringent requirements imposed on channel branching filters, *waveguide* circulators are predominantly used only at frequencies above 12 GHz. However, *stripline* circulators with coaxial connectors are preferred for the frequency range from 1.5 to 12 GHz. Compared with waveguide designs in this frequency range, they offer the advantage of compact dimensions and low manufacturing costs for comparable electrical characteristics. They will be discussed in greater detail below.

Fig. 5 indicates the basic design of stripline circulators: two ferrite disks, preferably circular in shape, are placed between two surfaces at ground potential and are separated from each other by a conducting (non-magnetic) center plate, around the circumference of which the ports are arranged 120° apart.

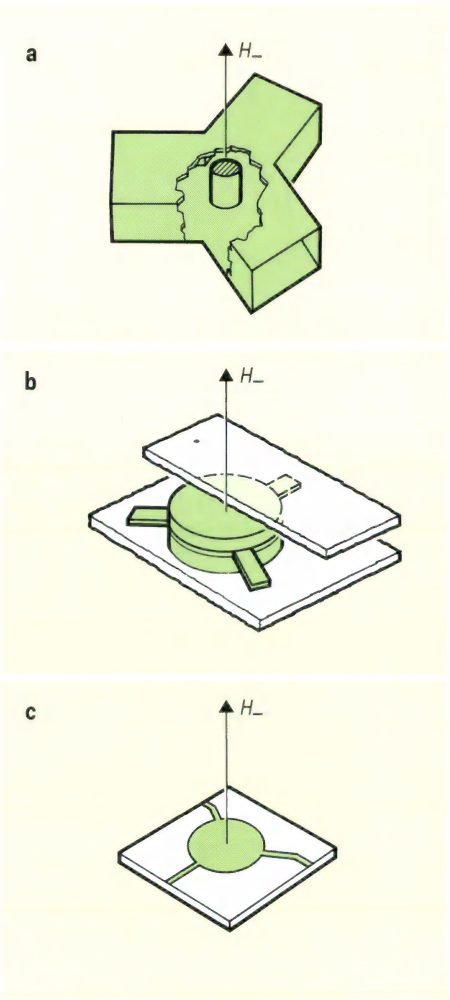


Fig. 5 Junction circulator designs
a Waveguide technology
b Stripline technology
c Microstrip technology

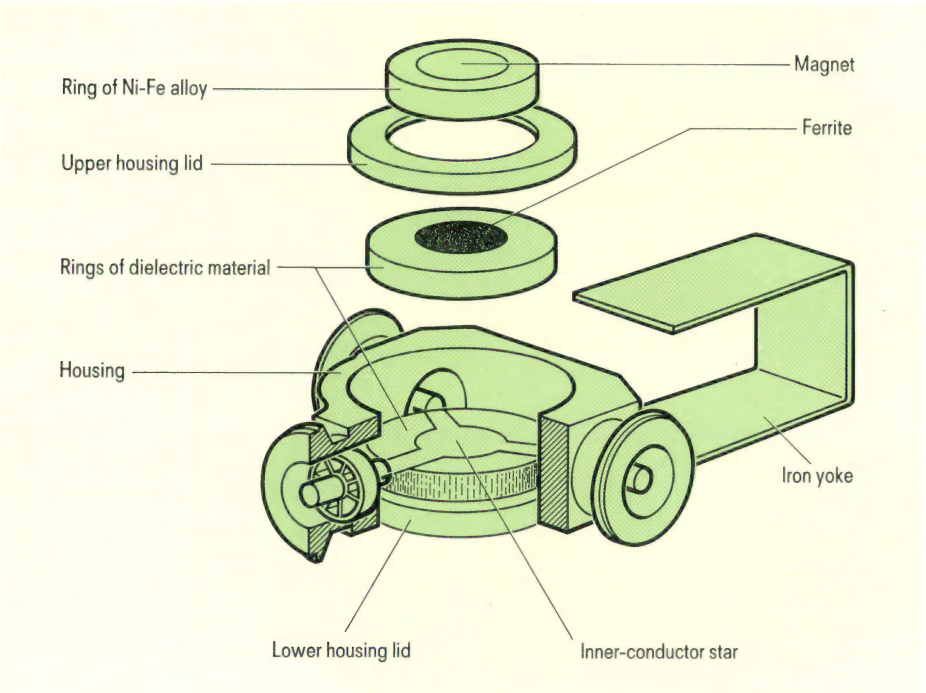


Fig. 6 Mechanical design of a channel branching circulator in stripline technology, with coaxial connections

An externally applied constant unidirectional magnetic field provides the required magnetic bias in the axial direction of the ferrite cylinders [4].

Design and adjustment of channel branching circulators

Fig. 6 shows a typical design for a Y-junction circulator realized in stripline technology, as used in channel branching filters for radio relay systems in the frequency range from 1.5 to 8.5 GHz. In addition to the usual characteristics of stripline circulators, this design also has a few special features: for example, the hot-pressed brass part forming the circulator housing has been additionally machined to ensure the required accuracy, and its surface is silver-plated to minimize losses. The outer conductors of the coaxial flange connectors are designed as an integral part of the housing in order to prevent possible RF shielding problems at this critical point. A star-shaped stripline junction is soldered onto the center conductors of the coaxial connectors and, as mentioned above, a ferrite disk is placed concentrically on each side of the junction and attached by spot bonding. Together with the two housing lids, the three feed lines of the inner conductor star each form a stripline. In order to match the usually low input impedance of the ferrites to the 50-Ω characteristic impedance customary for coaxial lines in microwave applications, these lines are also designed to form $\lambda/4$ transformers. A ring of dielectric material around the ferrite disks helps to keep these lines short so that compact designs are possible down to about 1.5 GHz.

The magnetic bias for the ferrite required for circulator operation is produced by the closed circuit of a permanent magnet consisting of two steel magnets on either side of the housing and an iron yoke for the magnetic return path. The housing lids of silver-plated iron also act as pole shoes for the magnetic circuit. In order to compensate for the dependence of the circulator's electrical specifications on the temperature-sensitive magnetic characteristics of ferrite materials, each magnet is surrounded by a ring of iron-nickel alloy acting as a temperature dependent magnetic shunt. This enables the effect of the operating temperature on the circulator's electrical specifications to be minimized.

Numerically-controlled machining of the housing and the use of special assembly gauges and bonding devices ensure extremely high-precision circulator fabrication. However, it is advisable to allow for a small amount of post-assembly tuning in order to meet the exacting requirements placed on circulators in channel branching filters. Tuning screws in the area of the coaxial lines permit matching to minimum reflection coefficients during final inspection in the test department. However, before this can be carried out, the constant magnetic field must be adjusted to a defined value. For this purpose, the circulator is subjected to a decreasing 50-Hz alternating field; this also stabilizes the magnetic circuit and effects physical aging of the magnets.

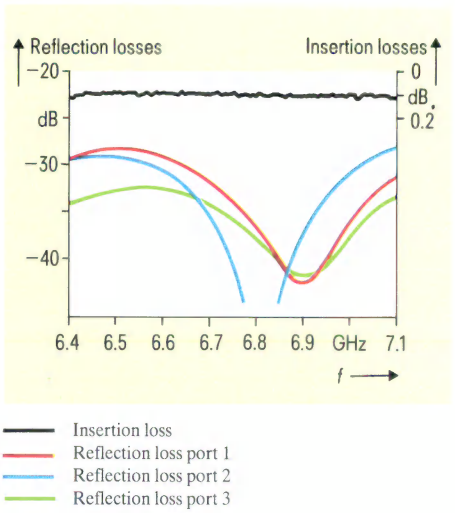


Fig. 7 Reflection losses at ports, 1, 2 and 3, and insertion losses a_D of the channel branching circulator for the DRS 140/6700 digital radio relay system plotted as a function of frequency

Measurement results

When employed in channel branching filter chains, the circulators must have input reflection coefficients below 5% and exhibit extremely low insertion loss in the order of 0.1 dB over the effective band and within a temperature range from 0 to 60°C. However, in this case only relatively small bandwidths of up to 30% are usually required. **Fig. 7** shows measured responses of reflection coefficients and insertion losses of a channel branching filter circulator for the DRS 140/6700 system. These curves clearly demonstrate the excellent electrical properties.

Future prospects

In conclusion, radio relay channel branching filter technology can be said to have fully matured. The design incorporating circulators with band-pass filters has overtaken earlier solutions, such

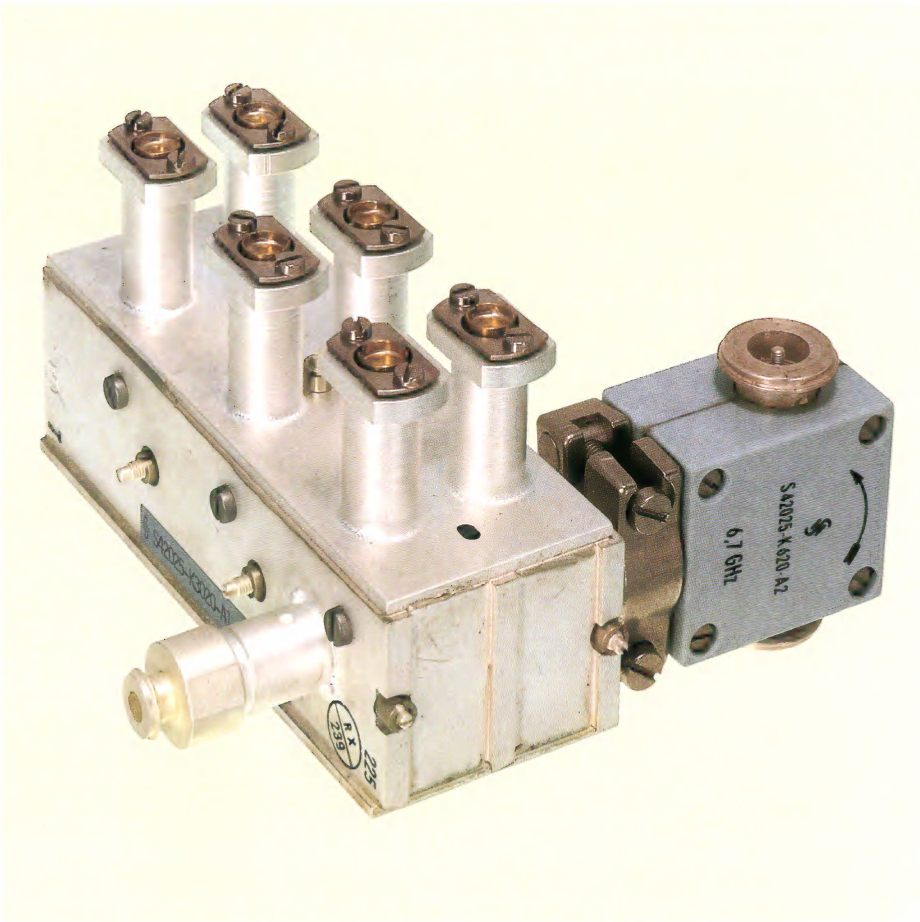


Fig. 8 Channel branching filter comprising a band-pass filter and a circulator for the DRS 140/6700 digital radio relay system

as hybrid junctions with band-pass filters or even band-stop filters. In the last decade, coaxial connector and transmission line technology has proved superior up to very high frequencies. A typical example of this is the channel branching filter for the DRS 140/6700 wideband radio relay system shown in **Fig. 8**.

The problem area indicated under the heading, *Loss analysis*, involving the relationship between losses and volume may in the future produce some new solutions, e.g. the use of dielectric materials. When line resonators are filled with dielectric material, shorter dimensions can be chosen for the same Q factor; for example, for lossless filling, the Q is inversely proportional to the 4th root of the dielectric constant in the direction of each axis, and the volume can be made correspondingly smaller. However, tuning over one half or the whole of each of the radio relay frequency bands is not easy to accomplish when the resonators are filled with dielectric material.

Dielectric resonators whose electromagnetic field extends into the surrounding space exhibit only dielectric losses. Their positioning creates problems: first, in respect of the screening walls always required which cause additional current losses, and second, in respect of each other. The latter is a problem because of the need to achieve the required coupling figures accurately. The resultant high design cost for a stable support and the small tuning range have so far made it difficult to use dielectric materials in channel branching filters.

Selective design measures may also improve spurious mode suppression for correspondingly increased volumes. In special cases, this could pave the way to even higher Q factors and consequently lower losses.

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Eberhard Schuegraf and Richard Schuster

New Types of Microwave Diplexers for Dual-Band Radio Relay Antennas

In the radio relay antenna field, the increasing demand for communication links has led to multiple utilization requirements going beyond dual polarization operation. A new generation of radio relay antennas has been designed for simultaneous operation in *two* RF bands, each with orthogonal planes of polarization, without loss of performance compared with conventional single-band antennas. This reduces costs and mounting space on radio relay towers for parabolic and shell-type antennas with apertures of as large as 3 to 4 m.

This quadruple utilization of the antennas requires a quadruplexer whose innovative design and cost-effective manufacture are described in this article.

In contrast to single-band antennas, a dual-band antenna requires a new type of diplexer with the following additional capability: signals fully occupying two RF bands at different frequencies with two planes of polarization in each band must be fed from four separate ports of the diplexer to the common port of the dual-band antenna as pairs of orthogonal plane-polarized signals. **Fig. 1** shows a typical solution in the form of a new type of system diplexer (quadruplexer) for the RF bands, 2.1 to 2.3 GHz and 3.4 to 3.6 GHz. This device contains four low-loss channel runs ($\alpha_0 \leq 0.03$ dB) with reflection coefficients of up to 3% from its four separate inputs on the equipment side to the common circular waveguide port of the dual-band antenna. Each run is isolated from all the others by more than 58 dB. The new diplexer – characterized by a compact design not achieved before – consists of only five components manufactured with extreme precision and cost-effectiveness using modern, computer-controlled milling methods. It is reduced in volume and requires no further electrical adjustments. In conjunction with channel branching filters as described

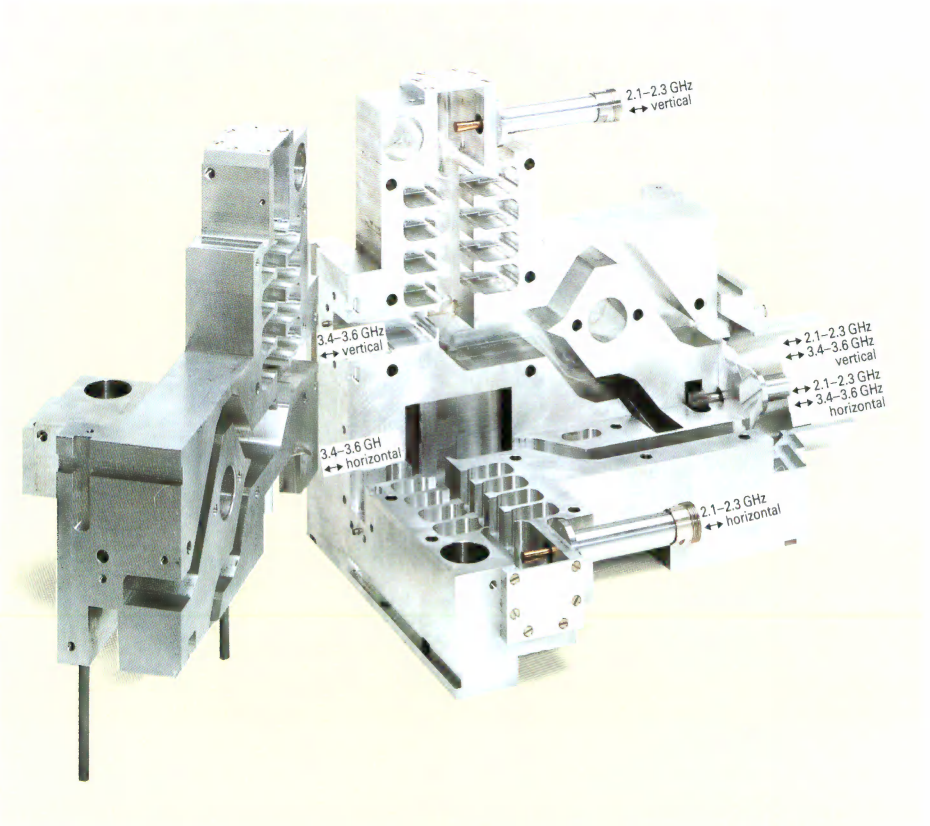

Fig. 1 System diplexer for the two RF bands, 2.1 to 2.3 GHz and 3.4 to 3.6 GHz, with orthogonal planes of linear polarization in each band (the photograph shows the diplexer opened out)

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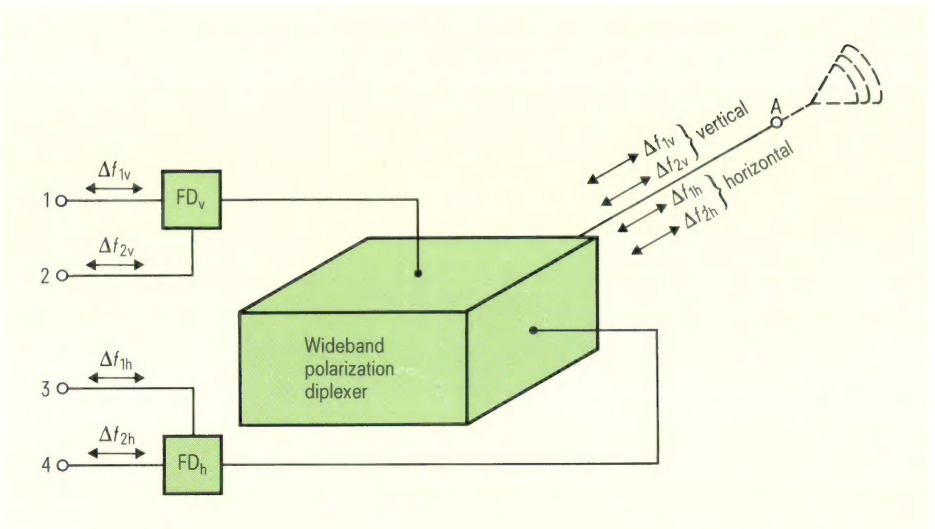
in [1, 2], this diplexer can connect up to 32 separate RF channels to a single antenna.

The operation of the new system diplexer as a combined polarization and frequency diplexer is illustrated by the basic circuit diagram in **Fig. 2**. The main component is a new polarization diplexer with a much greater bandwidth than generally used previously. The first separate port of a polarization diplexer is connected to one linearly polarized wave in a circular waveguide, while another wave in a plane orthogonal to that of the first in the same waveguide is connected to its second separate port. The polarization diplexer described below performs this function not just in one, but in two RF bands which may be relatively widely spaced. Two such RF bands, Δf_{1v} and Δf_{2v}, from separate feeders, 1 and 2, are combined onto one line by a frequency diplexer, FD_v, and passed by the wideband polarization diplexer as vertically plane-polarized signals to its common port A. Similarly, the two other RF bands, Δf_{1h} and Δf_{2h}, are fed from their separate ports, 3 and 4, via frequency diplexer, FD_h, to the common port A of the polarization diplexer in a horizontal plane of polarization. Consequently, all four bands concentrated at common circular waveguide port A can be passed on with excellent mutual isolation to the radiator of the dual-band antenna, typically a wideband corrugated horn.



Δf RF bands FD Frequency diplexer

Fig. 2 Principle of the system diplexer

Wideband polarization diplexer

High-quality microwave antennas for radio relay applications [3] can currently be implemented for bandwidths up to $f_h/f_l = 2$ (f_h being the highest operating frequency, f_l the lowest). The polarization diplexers must also have appropriate wideband characteristics in order to allow dual utilization of these antennas with two mutually orthogonal linear polarizations on a general basis. However, at present bandwidths of only up to $f_h/f_l = 1.24$ can be achieved with tolerable reflection coefficients around 2%. Consequently, the development of polarization diplexers with a much greater bandwidth than previously achieved is a significant contribution to improved utilization of wideband microwave antennas.

In the application discussed here, the new polarization diplexer must cover the frequency bands, 2.1 to 2.3 GHz and 3.4 to 3.6 GHz, with a total bandwidth of $f_h/f_l \approx 1.714$. The main component of this polarization diplexer is the double junction described in [4]. This junction branches the circular waveguide symmetrically into four ridge waveguides as shown in **Fig. 3**. The geometrical length of the ridge waveguides is very short, making them easy to manufacture. Considerable advantages result from the symmetry of the double junction in that – unlike virtually all known polarization diplexers – its two paths are identical (halving the development effort) and both are precisely symmetrical in phase. This offers considerable advantages for the circular polarization frequently employed in satellite communications.

Fig. 3 View inside the double junction

When fed spatially in-phase and equal-amplitude signals from pairs of opposite ridge waveguide ports, the double junction excites the orthogonal TE_{11} polarizations with electrical symmetry in the circular waveguide. Interfering TM_{01} and TE_{21} modes are not excited. The lowest interfering mode in the circular waveguide is the TM_{11} mode. The ratio of the cutoff wavelengths for TE_{11} and TM_{11} modes gives a theoretical bandwidth for the double junction of $f_h/f_l = 2.08$, which is adequate for most applications.

In addition, the double junction is suitable for a simple transformation of the characteristic impedance. As in all polarization diplexers, the characteristic impedances of the rectangular waveguide ports with the usual aspect ratio of $a = 2b$ differ from those of the circular or square waveguide with a ratio of $a = b$ by a factor of 2. This characteristic impedance discontinuity is matched immediately preceding the double junction (**Fig. 3**) by a coaxial $\lambda_H/4$ long waveguide transformer designed simply as a centrally located inner conductor cylinder, which is equally effective for both planes of linear polarization. For this purpose, the main inhomogeneity caused by the confluence of each of the mutually isolated ridge waveguides in the immediate vicinity of the transformer is also utilized. Wideband matching of the double junction is considerably facilitated by the fact that these inhomogeneities are spatially close

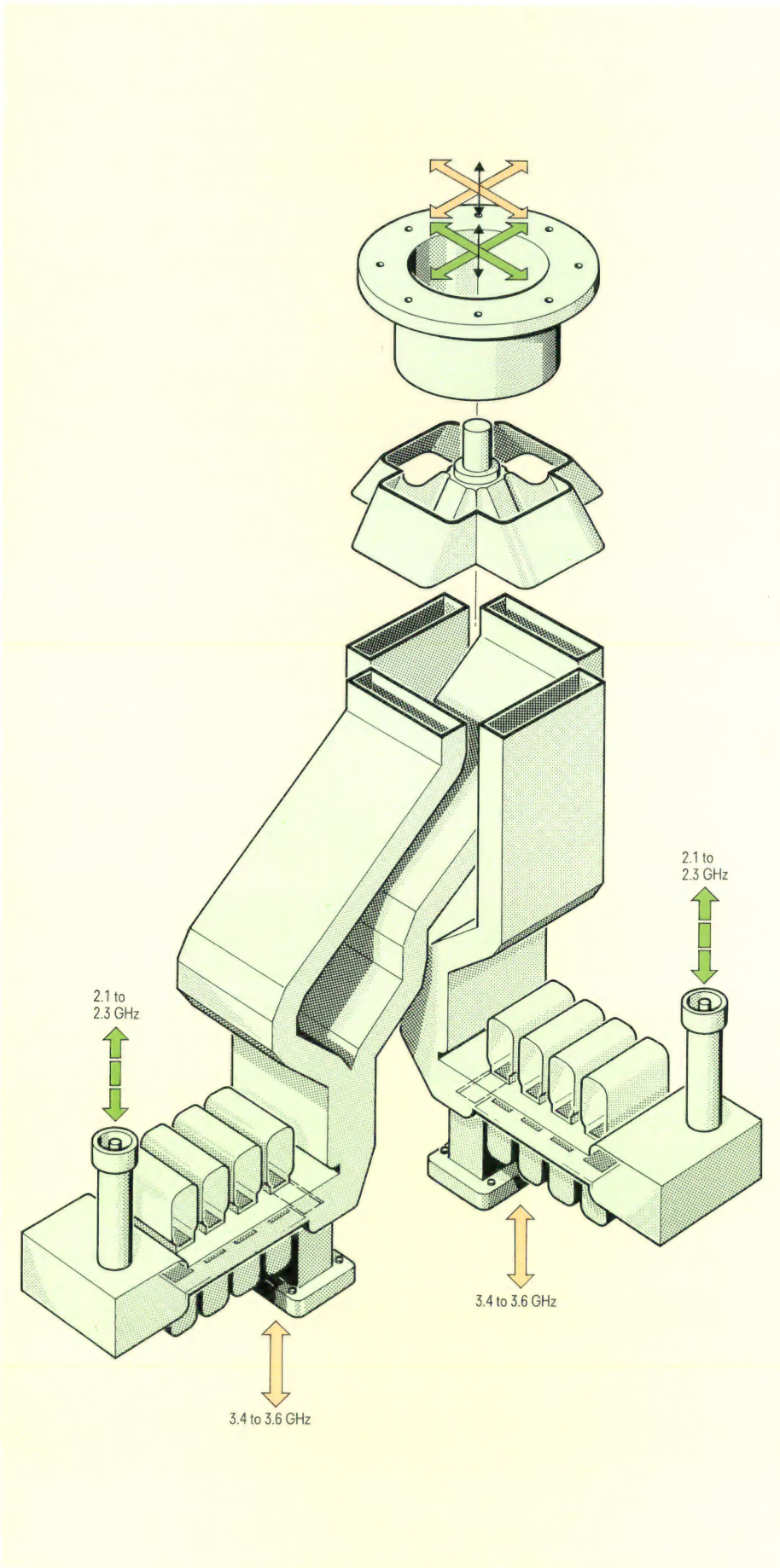


Fig. 4 Mechanical design of the system diplexer

together, and that all the remaining structure of the polarization diplexer is designed to present a homogeneous characteristic impedance.

The double junction is expanded to form a complete polarization diplexer as follows: the opposite pairs of ridge waveguide ports in the double junction (**Fig. 4**) are fed pairs of component waves of equal amplitude, in the same spatial direction and in phase. This is achieved by means of two symmetrical rectangular hybrid junctions, the first of which is symmetrically designed with straight branches. The electrically symmetrical second junction has two branches which – as shown in **Fig. 4** – are angled forward to the left in parallel with each other.

Each of the two hybrid junctions starts with a symmetrical series T. This splits the rectangular connecting waveguide with $a = 2b$ into two equal branches with $a_T = 4b_T$ with correct characteristic impedance over a wide band and bends them symmetrically apart to the left and right. These series Ts have a very low reflection coefficient over a wide band because they consist of pairs of equal *TM*-plane bends with extremely wideband compensation in the rectangular waveguide with $a_T = 4b_T$ [4]. A further *TM*-plane bend occurs in each branch of the series T, but in opposite directions. The distance between adjacent *TM*-plane bends is chosen such that the broad wall of one of the branches of the angled hybrid junction fits between the branches of the straight hybrid junction.

The branches of the series T on the angled hybrid junction are extended by two *TM*-plane offsets of rectangular waveguide with $a_T = 4b_T$. The *TM*-plane offset consists of two further opposite-direction *TM*-plane bends of the type described above, interconnected by a homogeneous waveguide with $a_T = 4b_T$. The length of the latter is chosen such that the lateral offset is large enough relative to the other hybrid junction to ensure that these two hybrid junctions fit within each other without mutual interference. Another important factor is to ensure that adjacent *TM*-plane bends are spaced sufficiently far apart [4].

Overall, the new polarization diplexer principle meets all the requirements for very large bandwidths, because only low-profile *TM*-plane bends with a par-

ticularly wide bandwidth, homogeneous lines and very short ridge waveguides are used, and these components are easy to manufacture.

Fig. 1 (right-hand side) shows a practical application of the new polarization diplexer principle outlined in **Fig. 4** for the RF bands around 2.2 and 3.5 GHz. The reflections in this polarization diplexer are $r < 1.5\%$ in the frequency band, 2.1 to 2.3 GHz, and $r < 2\%$ in the frequency band, 3.4 to 3.6 GHz, with polarization discriminations greater than 58 dB and 72 dB, respectively, in these bands.

Frequency diplexer

Fig. 4 (bottom) shows the two frequency diplexers, which are particularly suitable for combining with the polarization diplexer described above. The frequency diplexer comprises a special *TM*-plane junction with three rectangular waveguide branches. The advantage of this is that it will not excite a TE_{20} interfering mode, but only a TM_{11} interfering mode which enables a large single-mode frequency range to be used. A waveguide band-rejection filter for the upper frequency band is connected to the *TM*-plane junction. This four-section rejection filter provides stop-band attenuation of more than 75 dB over the band from 3.4 to 3.6 GHz and reflections of less than 1% as well as losses of <0.03 dB in the range of 2.1 to 2.3 GHz.

The waves in the lower frequency band from 2.1 to 2.3 GHz travel in the frequency diplexer from the coax-waveguide transition through the waveguide band rejection filter into the upwardly-angled branch containing both frequency bands. The narrower, downward-pointing rectangular waveguide ($a = 58.17$ mm, $b = 29.08$ mm) presents a strong aperiodic attenuation to the waves in the lower frequency band. The waves in the frequency band, 3.4 to 3.6 GHz, pass through the narrower rectangular waveguide (in **Fig. 4** from the bottom) and travel up through the branch for both bands. This behavior is supported by the short-circuit action of the 3.5-GHz rejection filter. The high rejection of this filter prevents a leakage from the 3.4-GHz to 3.6-GHz band into the coaxial ports for the 2.1-GHz to 2.3-GHz band.

Polarization/frequency diplexer (system diplexer)

The system diplexer is formed by directly connecting a frequency diplexer of the type described earlier to each rectangular waveguide port of the wide-band polarization diplexer. The physical design of both the frequency diplexer and the associated hybrid junctions in the polarization diplexer is such that, when interconnected, the planes without transverse current coincide. In these planes, the network is divided into two symmetrical halves. Thus, the entire inherently *plane* structure comprising the frequency diplexer and the hybrid junction can be manufactured extremely accurately and cost-effectively by means of a numerically-controlled milling process. Because it can be made in one piece without any internal waveguide flange connections, the complete system diplexer consists of only five components, i.e. the double junction and the two pairs of symmetrical halves of the two hybrid junctions with frequency diplexers.

Fig. 1 shows the system diplexer opened up. The *vertical* section shows the upwardly-angled hybrid junction connected to the double junction (with the circular waveguide branch on the right). The four-section, 3.5-GHz rejection filter of the associated frequency diplexer is angled upwards; its rectangular waveguide port for the frequency band, 2.1 to 2.3 GHz, points upwards and leads to the transition into a 7/16 mm coaxial cable. The signal from this port is used to excite in the circular waveguide branch of the diplexer (**Fig. 1**, right) the TE_{11} mode in the polarization plane which is identical with the associated dividing plane – this is the vertical plane of linear polarization in the 3-dimensional view of the diplexer. Linear vertical polarization is also produced in the circular waveguide branch of the diplexer in the 3.4- to 3.6-GHz band by the signal from the waveguide port located above the center axis in **Fig. 1** (left). This port has an $a \times b$ cross section of 58.17 mm × 29.08 mm.

The *horizontal* dividing plane (**Fig. 1**) shows the front portion of the straight hybrid junction. Connected to this is the second frequency diplexer with the upwardly angled, 3.5-GHz rejection filter and the waveguide-coax transition. The signal from here excites the linear horizontal polarization in the frequency band, 2.1 to 2.3 GHz, in the circular waveguide branch of the diplexer. Horizontal TE_{11} polarization is likewise excited in the 3.4- to 3.6-GHz band by the rectangular waveguide port which is on the longitudinal axis of the diplexer in **Fig. 1** (bottom left). It also has an $a \times b$ cross section of 58.17 mm × 29.08 mm.

The system diplexer has a total of four channels running from the four separate ports for transmitters and receivers to a common circular waveguide port for the dual-band antenna and vice versa. The reflections in these four channels are measured at the relevant separate port, while the circular waveguide branch (96 mm diameter) is terminated by a matched load. The reflection coefficients are $r \leq 3\%$ at both coaxial ports (2.1- to 2.3-GHz band) and $r < 2.5\%$ at the two rectangular waveguide ports (3.4- to 3.6-GHz band).

The polarization discrimination between the two coaxial ports, with the circular waveguide branch of the system diplexer terminated so as not to affect the polarization, remains greater than 58 dB, and greater then 72 dB at the two rectangular waveguide ports for the 3.4- to 3.6-GHz band. These discrimination figures are no different from the values specified for the polarization diplexer on its own. The isolation between the ports for different frequency bands with the same plane of polarization is greater than 75 dB. Total insertion losses are less than 0.03 dB.

The installation in a standard shell-type antenna poses no problems, since the entire system diplexer is only 361 mm long and the maximum lateral dimension is 380 mm. Dual-band antennas equipped with a system diplexer of this kind have already been operated successfully.

In addition to the system diplexer for the RF bands around 2.2 and 3.5 GHz described here, similar diplexers are available for the following additional combinations of RF bands:

- 3.6 to 4.2 GHz
and 5.925 to 6.425 GHz;
- 3.58 to 4.2 GHz
and 6.425 to 7.125 GHz;

- 10.95 to 11.7 GHz,
12 to 12.5 GHz
and 14 to 14.5 GHz;
- 19.7 to 20.2 GHz
and 29.5 to 30 GHz.

Manufacturing method

The manufacturing method for these diplexers has been adapted to provide the optimum channel runs described earlier and loss-free splitting of the mechanical design. Working from the dividing planes, which are free from any transverse current, and all of which bisect the waveguides along the center line of their broad walls, two waveguide halves with the same minimum depth are produced. For this reason, the milling cutter wears by an equal amount during the manufacture of the two waveguide halves so that the dimensional deviations on both halves are also similar. Consequently, both halves are very accurate mirror images, which leads to extremely small displacements in the dividing planes.

Once the two symmetrical parts have been milled, they are screwed together and special fitted bolts ensure congruent matching of associated line halves. The matching holes required for this purpose can be produced in the same operation during milling of the line channels. This ensures the smallest possible offset between the channel halves. The channels for the straight hybrid junction are then milled into the paired parts. Lastly, these likewise symmetrical parts are fixed in position and screwed together. The positional fixing is achieved as before by means of fitted bolts in milled matching holes. To ensure that these four parts, screwed together to form one block, have a high quality of flatness at the mating surfaces, they are jointly retouched.

The elimination of any electrical matching on these diplexers in the test department demands certain tolerance requirements for waveguide profiles and longitudinal dimensions. They can be most cost-effectively met by means of a track-controlled milling process. In order to minimize warping of components during processing, they are clamped without strain for the milling process. For this purpose, the clamping devices are arranged such that after the waveguide contours have been milled, the upper face of the waveguide halves can also be milled without changing the clamps. In this manner, the waveguide halves can be produced with the greatest possible accuracy with respect to the depth of the profile and, consequently, of the broad wall (a) of the waveguide. This also ensures very high quality in terms of flatness, thereby minimizing the remaining gap in the mating planes.

The double junction branching the circular waveguide into four symmetrically oriented ridge waveguides is an important connecting element between the diplexer block and the circular waveguide. The structure of the double junction allows very short ridge waveguides to be used. Special devices and tools enable these relatively simple profiles to be fabricated with even greater cost-efficiency.

The continuous interior space of the system diplexer is filled with dry air under low excess pressure to prevent any ingress of moisture and the formation of condensation water. Simple and tested sealants can be used to obtain very good seals as a result of the favorable external shape of the joints. The material used for these combiners is AlMg 4.5 – which is climatically stable and therefore suitable for open-air installations. Since it is a stress-relieved material it falls into the group of aluminum alloys with low warpage characteristics. Another advantage for use on radio relay towers is its low specific gravity.

Experience with manufacturing system diplexers by means of computer-controlled milling has shown that the exacting specifications can be met without any test department adjustment of the individual diplexers. Consequently, the complete diplexer has no adjusting screws whatsoever. The computer-controlled milling process has given excellent results in the fabrication of such complicated waveguide circuits.

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Jan Steinkamp and Wolfgang Ulmer

The Spectrum of Analog Radio Relay Systems

Analog radio relay networks based on radio relay systems employing frequency modulation have remained an essential component in communications throughout the world. A varied spectrum of systems has been developed for such networks with differing characteristics for long-haul and medium-haul use and for the transmission of frequency-division multiplex voice channel blocks or TV signals.

This article provides an overview of the entire range of systems and equipment covering the radio relay frequency bands from 300 MHz to 11.2 GHz. The authors first discuss the basic design of different system versions for direct and indirect modulation and the demands placed on the system components. They then present the wideband and narrowband systems developed for the different frequency bands in the long-haul and medium-haul networks with the associated modulation and service channel equipment.

Fundamentals of analog radio relay transmission

Analog radio relay systems are designed to ensure that the applied baseband signals, usually comprising several separate components, are transmitted with the minimum of distortion and additional noise. The systems employed for this purpose must meet certain transmission quality requirements which are derived from the permissible noise values for the model circuits specified by the CCIR (hypothetical reference circuits) [1].

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The basebands to be transmitted are either frequency-division multiplex (FDM) signals comprising up to 2700 voice channels or video signals for TV transmission. Additional signal carriers for sound programs or data signals up to 2 Mbit/s can be transmitted above the baseband. With FDM signals it is additionally possible to utilize the baseband frequencies up to the bottom edge of the FDM signal in order to transmit service channel, supervisory and control signals as well as additional FDM signals in up to a further 24 FDM channels.

For radio relay transmission, the CCIR has recommended channel arrangements in the radio frequency (RF) bands from 1.7 to 18.7 GHz allocated by the World Administrative Radio Conferences. For low capacity systems ($\leq$132 voice channels), there is provision for narrow bands below 1.7 GHz, but there are no recommendations on channel arrangements [2]. The frequencies used for analog radio relay systems have until now been confined almost exclusively to the band from 300 MHz through 13 GHz. At higher frequencies the effect of rain attenuation is so serious that analog systems can only use these frequency bands in special applications.

The method of modulation most widely employed is frequency modulation (FM). Single-sideband amplitude modulation (SSB-AM), being the method with the highest bandwidth efficiency, is extremely attractive indeed. However, SSB-AM is less favorable than FM in dense networks, such as those generally found in Europe, because of the high sidelobe suppression required. In addition, the sensitivity of SSB-AM to selective fading entails significantly greater equipment complexity due to the dynamic amplitude equalization required. As a result, SSB-AM systems have to date been used only in special applications [3] or on high-density trunk routes in extremely long links with few drops (e.g. coast-to-coast links in the USA) [4].

Analog radio relay systems for the different network levels

Frequency-modulated radio relay systems can be divided into two major groups:

- systems employing indirect modulation and intermediate frequency (IF) through-connection for the transmission of wide basebands ($\geq$960 voice channels and TV),
- systems employing direct modulation of the RF carrier and baseband through-connection for the transmission of narrow basebands ($\leq$960 voice channels and TV to less exacting requirements) for medium-haul and special-purpose networks.

The radio frequency bands recommended by the CCIR are assigned to these two groups of systems as shown in the system overview in **Table 1**. It shows the range of analog radio relay systems available from Siemens together with system data relating to type of modulation, radio frequency and transmission capacity. It can be clearly seen that the systems with up to 300 voice channels are all directly modulated, while higher-capacity systems all employ indirect modulation.

The basic configuration of analog radio relay links employing indirect and direct modulation is shown in **Fig. 1**. With indirect modulation, the frequency modulation or demodulation occurs in modem equipment separate from the radio

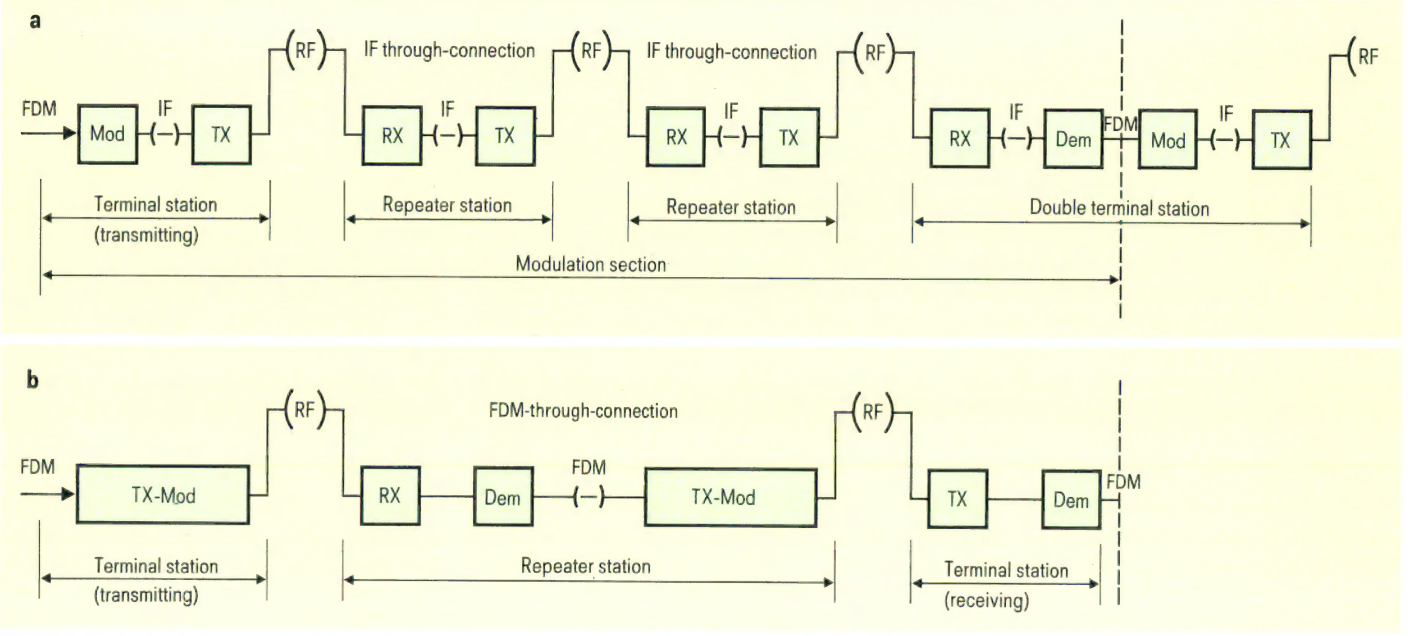
Number of voice channels \ Radio frequency in MHz	235 to 360	344 to 476	796 to 960	1700 to 1900	1900 to 2300	2100 to 2300	3400 to 3600	3800 to 4200	5925 to 6425	6425 to 7125	7125 to 7425	7425 to 7725	8200 to 8500	10700 to 11700	12750 to 13250
24	D	D	D								D				
72	D	D	D	D							D				
132			D	D							D	D			
300				D							D	D			
960					I			I*	I			I	I	I	I*
1260					I			I*	I			I	I	I	
1800								I*	I					I	
2700															
TV					I	I	I	I*	I		I	I	I	I	I*

D Direct modulation I Indirect modulation * Production ceased

Table 1 Summary of the spectrum of Siemens analog radio relay systems

units, whereas with direct modulation of the transmitter, the modem functions are generally integrated physically in the radio units. With indirect modulation, it is thus possible for repeater stations to be through-connected at IF (70 MHz or 140 MHz). This eliminates the noise contributions and distortion which would otherwise be introduced by the modem equipment. On long links it is usual to through-connect at IF on three to five repeater stations before returning to baseband, generally for reasons concerning network structure. The area of a radio relay link between two baseband interfaces is referred to as a modulation section.

By contrast, when the RF carrier is modulated directly in the transmitter, the receiving facility must inevitably demodulate, and the noise contributions and distortion due to demodulation and remodulation at each repeater station must be accepted. Indeed, in special-purpose networks there are advantages in having access to the baseband at repeater stations [5]. Even so, directly modulated systems are more suitable for the transmission of only moderately wide bands for the reasons given. As a result, they are employed mostly in medium-haul and special-purpose networks rather than in the long-haul network.



Dem Demodulator
FDM Frequency-division multiplex baseband
IF Intermediate frequency
Mod Modulator
RF Radio frequency
RX Receiver
TX Transmitter
TX-Mod Transmitter employing direct modulation

Fig. 1 Configuration of analog radio relay links employing indirect modulation (a) and direct modulation of the transmitter (b)

The spectrum of analog radio relay systems

Siemens' spectrum of analog radio relay systems is primarily oriented to the transmission requirements arising in densely meshed networks, such as that of the Deutsche Bundespost, and to the equivalent requirements in special-purpose networks (e.g. for electric utilities). The approach adopted in designing these systems was that optimum solutions can only be achieved if all the factors affecting radio relay transmission are taken into account as fully as possible. Development effort was, therefore, not confined to the radio and modulation equipment alone, but included all the components and ancillary facilities of importance in implementing the different levels of the transmission network. This aspect not only included antennas, branching filters, polarization diplexers, special waveguides and RF filters, but also data-above-baseband modems for additional transmission of digital signals at up to 2 Mbit/s, service channels units, protection switching equipment for radio relay paths or networks (TV program network protection switching), as well as power supplies for equipment and radio relay stations. **Fig. 2** shows a range of products meeting these requirements within Siemens' overall analog radio relay systems approach. It provides optimum solutions for transmission requirements in terms of reliability, transmission quality and economy as demonstrated convincingly by the success of these systems in major projects abroad, for instance in the Philipinnes, Nigeria and Oman.

FM wideband systems employing indirect modulation for the long-haul network

Table 2 provides a summary of the systems for the long-haul network together with the principal electrical characteristics. As previously stated, all these long-haul systems employ IF through-connection, the IF being 70 MHz in all systems. The only exception is the FM 2700/6700 wideband system which employs an IF of 140 MHz. The systems range in transmission capacity from 960 through 1800 to 2700 voice channels. Apart from the 6.7-GHz wideband system, all the systems can also be employed for TV transmission. The FM-TV/2200 and FM-TV/3500 systems developed specifically for TV transmission are rather special in that they employ relatively narrow channel spacings of 21 and 20 MHz [6, 7].

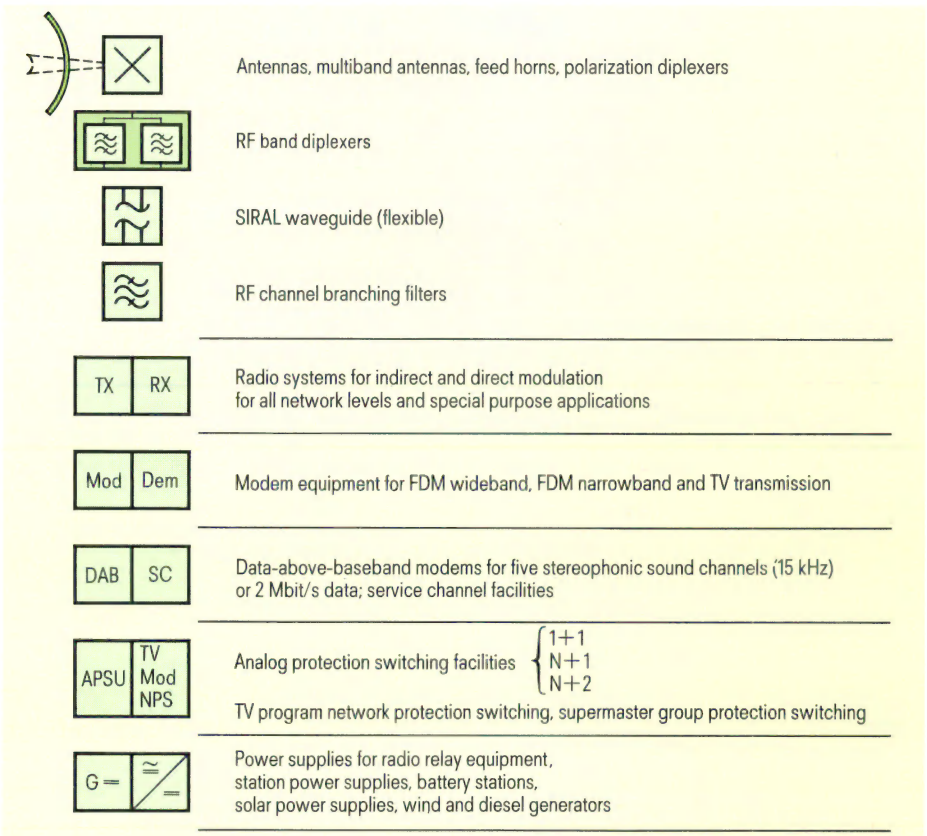
- *Except for the FM 960/6700-7500-8400 series of systems, all the systems employ the same circuit principle.*

This principle is illustrated by the functional diagram for the transmitter and receiver as typified by the FM 1800-TV/6700 R system shown in **Fig. 3**. The frequency-modulated IF signal fed to the transmitter is first limited and equalized, then translated to the RF band by an up-converter. The carrier frequency for the conversion is produced in a microwave oscillator incorporating a bipolar transistor. This oscillator is locked to a crystal frequency via a phase-locked loop. After the conversion, the wanted sideband is selected by a filter and then amplified in a semiconductor transmit amplifier to the transmit output power of 5 W. For higher transmit powers, as are required for instance on the FM 2700/6700 and FM 1800/11200 systems, traveling-wave tube amplifiers are used in place of semiconductor amplifiers.

In the receiver, the incoming signal undergoes low-noise preamplification and is down-converted to IF. It is then passed through an IF band-pass filter for adjacent channel suppression, an automatically controlled main IF amplifier and an equalizer to correct differential gain and to compensate group delay and attenuation distortion. The signal is then divided between two identical outputs which can be disconnected automatically if the path loss becomes excessive (squelch).

- *Unlike the systems described above, the radio units of the FM 960/6700-7500-8400 series of systems employ only one microwave carrier supply per radio assembly.*

In order to obtain the constant frequency separation between transmitter



APSU	Analog radio relay protection switching unit	RF	Radio frequency
DAB	Data-above-baseband modem	RX	Receiver
Dem	Demodulator	SC	Service channel equipment
FDM	Frequency-division multiplex	TV-Mod-NPS	TV program network protection switching
G	Generator	TX	Transmitter
Mod	Modulator		

Fig. 2 The Siemens spectrum of analog radio relay systems

and receiver, this equipment family thus requires a second frequency conversion in the transmitter [8, 9].

The rack configuration of FM wideband systems for FDM and TV signal transmission is shown with the appropriate ancillary equipment in **Fig. 4**. The first narrow rack (from left to right) has a receiver below with a transmitter above for each of the two TV systems, FM-TV/2200 and FM-TV/3500 (each in 54 mm wide narrow insets). The next rack is equipped with a receiver and a transmitter of the FM 1800-TV/6200 R system in the lower section and two transmit/receive insets of the FM 960-TV/6700-7500-8400 series of systems in the upper section. The adjoining rack contains (from bottom to top) a (1 + 1) baseband line protection switching unit for 300 to 2700 voice channels, surmounted by a (1 + 1) line protection switching unit with integral demodulators, and above that another such unit with integral modulators. In the adjacent racks a complete equipment assembly for the FM 2700/6700 wideband system can be seen on the right with receiver, transmitter preamplifier and final amplifier. On the left (at the top) is the associated connection unit and below it the associated modulator and demodulator (FM Mod 2700/140). The equipment insets mounted below them are an FM Mod 70/A modulation equipment and a 2-Mbit/s data-above-baseband modem DEG 2/7-10.

FM narrowband systems employing direct modulation for medium-haul and special-purpose networks

The narrowband systems presented here all employ direct frequency modulation of the transmit oscillator and baseband through-connection at repeater stations. As stated previously, the modulation and demodulation equipment is physically integrated in the radio units. A standard approach was adopted on all systems, with transmitter and receiver – including modem and power supply – mounted in 600 mm high and 110 mm wide style 7R equipment insets. As can be seen from the summary of electrical specifications in **Table 3**, these systems can be divided into three groups:

The first group comprises two systems in the 300-MHz and 400-MHz bands which can optionally transmit 3 to 24 or 72 telephone signals.

The space available below the baseband is used for transmitting a service channel signal at its original frequency (0.3 to 3.4 kHz) and the radio pilot. The transmit power (12 W on the 300-MHz system and 6 W in the 400-MHz system) is produced by transistorized power amplifiers [10].

The second group consists of a family of four systems in the 800-MHz, 1.8-GHz, 7.2-GHz and 7.5-GHz bands, each of which is available in different versions for various transmission capacities.

As indicated in **Table 3**, the 800-MHz system is designed for 24 to 132 voice channels, while the 1.8-GHz system is intended for 72 to 300 voice channels.

FM wideband radio relay system	RF range f_{min} f_{max} (MHz)	Number of voice channels	Adjacent channel separation (MHz)	RF channel pairs	Service channel (kHz)	12 FDM service channels (kHz)	Transmit power (W)	Noise figure (dB)	System Value (dB)	Center gap (MHz)
FM 960-TV/2100 R	1990 2300	960 TV (+ sound)	29	6	0.3 to 3.4	6 to 54	5	4	152.2 159 (149.4)	68
FM 1800/4000	3800 4200	1800 TV (+ sound)	29	6	0.3 to 3.4	6 to 54	10	9	140.7 156.5 (146.9)	68
FM 1800/6200 R	5925 6425	1800 TV (+ sound)	29.65	8	0.3 to 3.5	6 to 54	5	6.5	140.7 156.5 (146.9)	44.4
FM 960/6700	6425 7125	960 TV (+ sound)	40	8	0.3 to 3.4	6 to 54	1.2	7.5	142.0 148.8 (139.2)	60
FM 960/7500	7425 7725	960 1260 TV (+ sound)	21 (23.3)	10 (6)	0.3 to 3.4	6 to 65	1.2	7.5	142.0 139.4 148.8 (139.2)	28 (23.3)
FM 960/8400	8200 8500	960 TV (+ sound)	23.3	6	0.3 to 3.4	6 to 54	1.2	7.5	142.0 148.8 (139.2)	23.3
FM 2700/6700	6425 7125	2700	40	8			20	8	141.7	60
FM 1800/11200	10700 11700	1800 TV (+ sound)	40	12			18	9	143.8 159.6 (150.0)	90
FM-TV/2200	2100 2300	TV (+ sound)	22	4			3	4	156.8 (147.2)	48
FM-TV/3500	3400 3600	TV (+ sound)	20	4			2	4.5	154.5 (144.9)	40

Table 2 FM wideband radio relay systems for the long-haul network

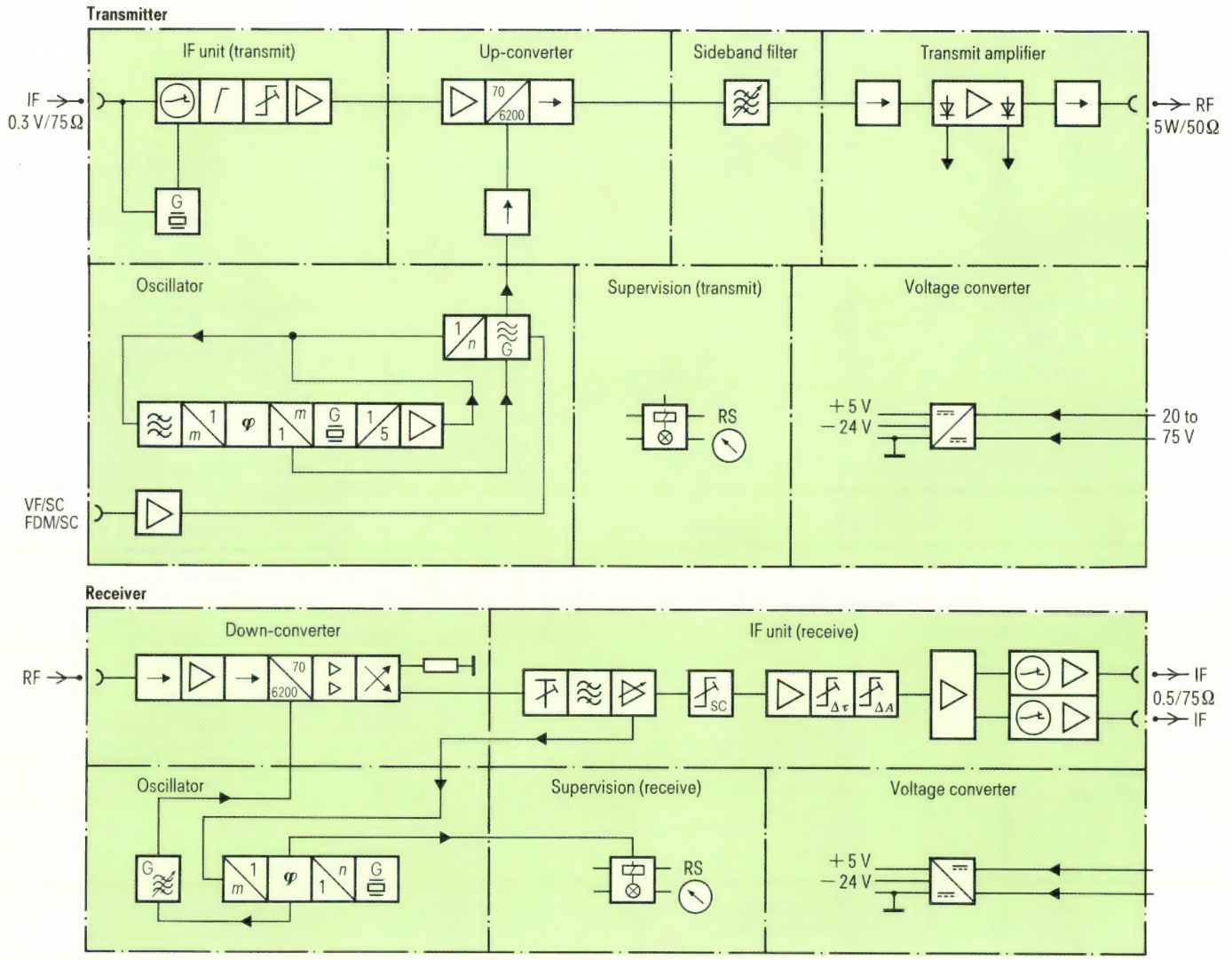
The two systems for the 7-GHz band can optionally transmit 132 or 300 telephone signals [11].

As is clear from **Fig. 5**, which shows a (1 + 1) configuration with two radio assemblies in a wall-mounted frame, a modular equipment design has been adopted for this series of systems. The transmitter and receiver, modulator input stage and demodulator as well as the power supply are each accommodated in replaceable slide-in units within the 600 mm high equipment inset. The equipment can thus be readily converted to different versions by replacing the radio cassettes (0.8, 1.8, 7.2 and 7.5 GHz) and the modem cassettes (24, 72, 132 and 300 voice channels). The electrical design for single operation of the 1.8- or 7.2- and 7.5-GHz systems is shown in the functional diagram in **Fig. 6**.

The baseband signal applied to the modem unit is first combined with the service channel and the radio pilot, and is then predistored in a preemphasis network optimized specifically for each modem version. It is subsequently fed via a linearization network to a varactor diode which directly modulates the frequency of a power oscillator operating at 1.8 GHz. In the versions for 7.2 and 7.5 GHz, this oscillator is followed by a frequency quadrupler. On the receive side, the incoming RF signal is first converted to IF. The local oscillator employed for this purpose is of basically the same design as the transmit oscillator and is stabilized by the same crystal-controlled circuit. The IF signal is then filtered, amplified and delay-equalized. After demodulation, the resultant baseband is first equalized in a deemphasis network. The service channel signal and radio pilot are removed from the baseband, which is then available again for through-connection at the output of the modem unit.

The third group of systems was specifically developed for use in special-purpose networks.

The radio units all operate at an RF of 7.2 GHz with versions available for 12, 24, 72 and 132 voice channels. The electrical design and mechanical construction are approximately the same as those of the units for 300 and 400 MHz.



FDM/SC	Frequency-division multiplex service channel circuit	IF	Intermediate frequency	SC	Service channel equipment
G	Generator	RF	Radio frequency	VF/SC	Voice-frequency service channel
		RS	Remote supervision		

Fig. 3 Functional diagram for transmitter and receiver as typified by the FM 1800-TV/6200 R system

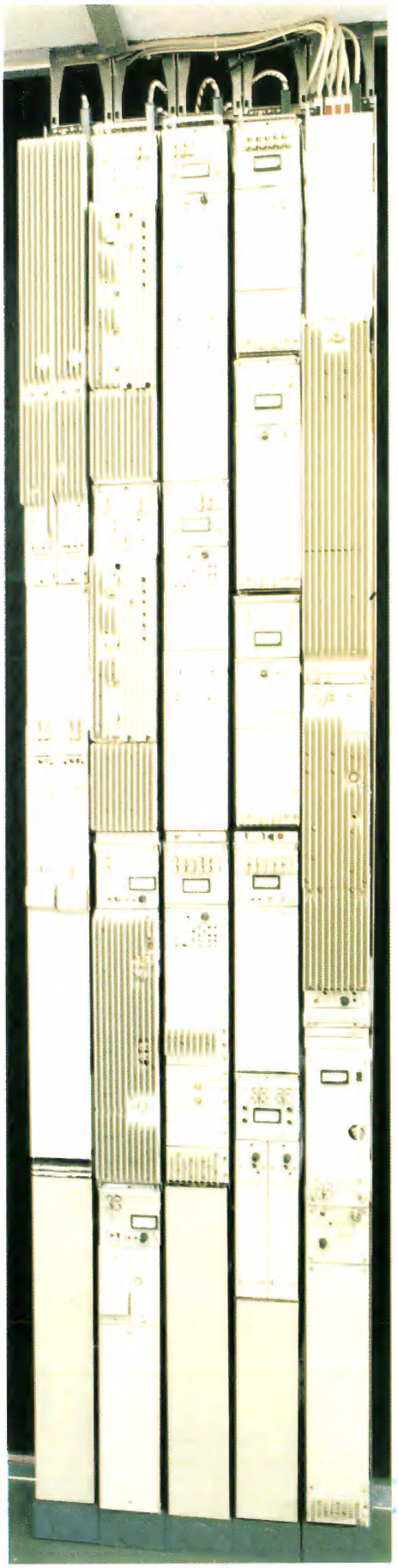


Fig. 4 Rack configuration of wideband analog radio relay systems

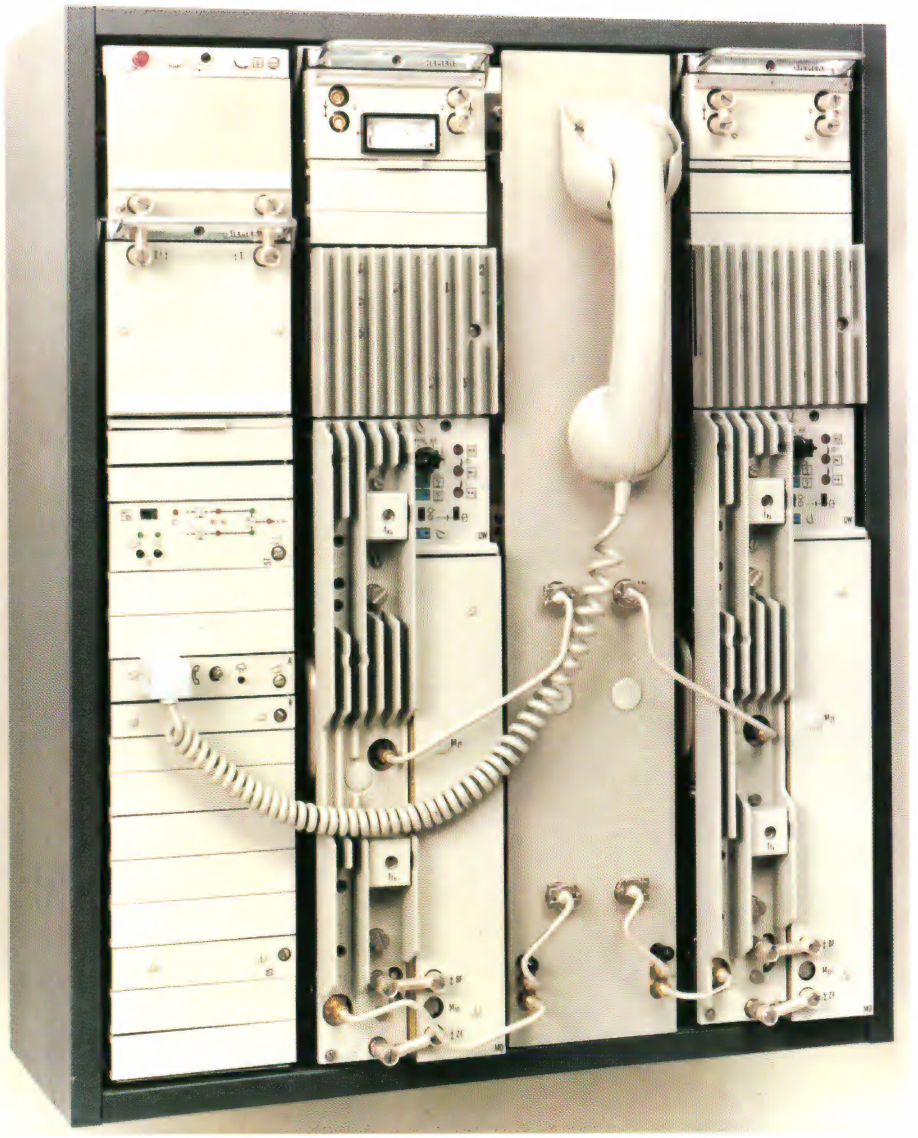


Fig. 5 Configuration of a narrowband radio relay system in the wall-mounted frame with the (1+1) protection switching unit, two radio units and a channel branching filter

Ancillary equipment and components

In keeping with the basic approach previously described (**Fig. 2**), the range of Siemens equipment for analog radio relay systems includes all the ancillary equipment and components required for establishing networks at the various levels. Following the order of listing used in **Fig. 2**, this comprises:

Antennas

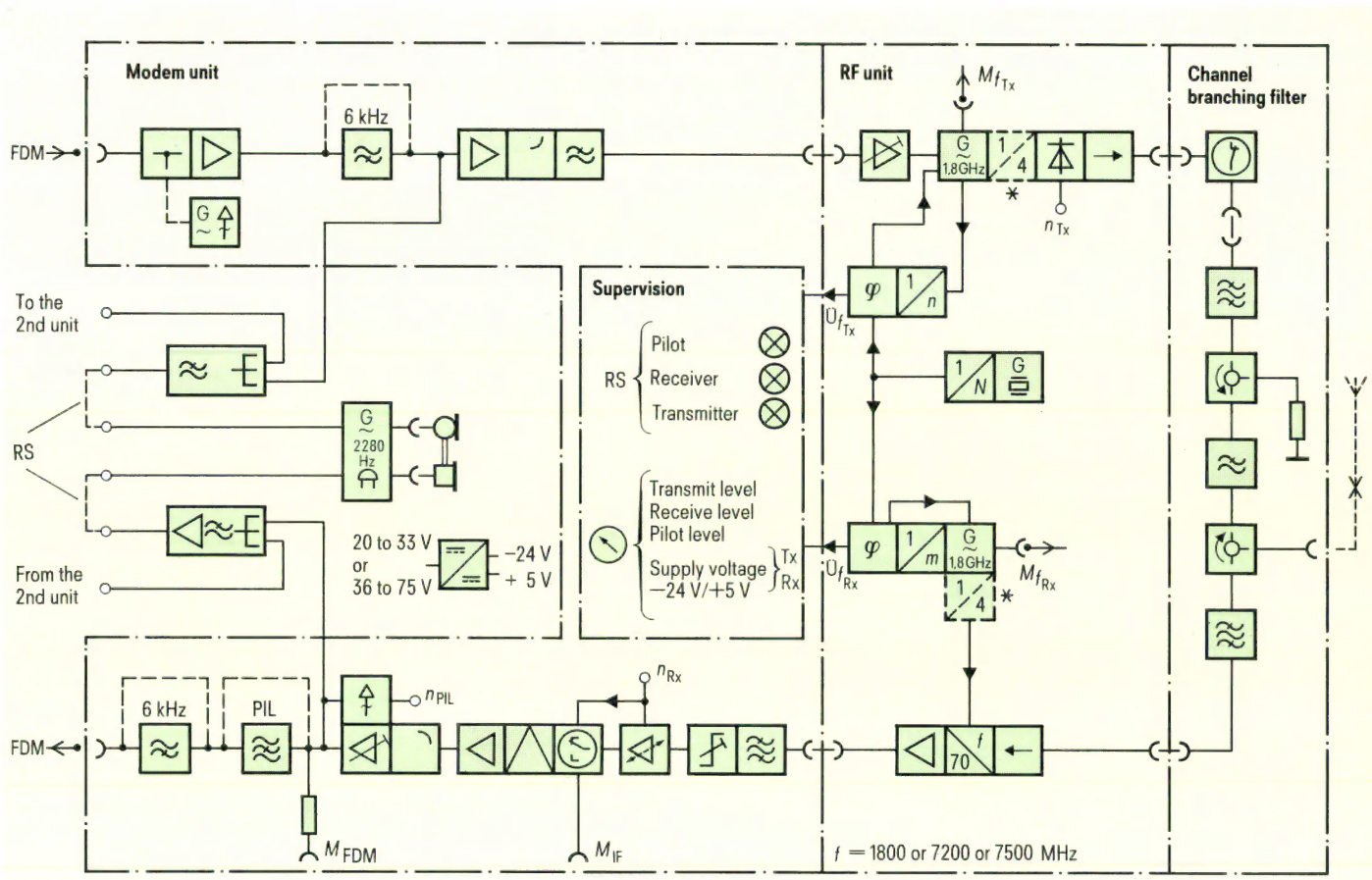
A complete range of parabolic and shell-type antennas is available for use at all network levels in the frequency ranges, 1.7 to 20 GHz and 2.1 to 12 GHz, respectively, each with polarization diplexers for emitting and receiving both polarizations. During development, particular emphasis was placed on high sidelobe suppression and high cross-polarization discrimination as is required in densely meshed radio relay networks. In addition, there are two-band antennas available, e.g. for 2.2 and 3.5 GHz (antennas for 3.9/6.7 GHz and 3.9/6.2 GHz are in preparation) [12]. Radiation-coupled dipole-array antennas and corner-reflector antennas have been developed for the frequency range below 1500 MHz [13].

Frequency band diplexers

Multiband antennas often provide crucial advantages in station construction in view of the shortage of antenna mounting space on radio relay towers and contribute significantly to the cost-effectiveness of radio relay links. Novel frequency band diplexers providing high isolation between frequency bands and polarizations (80 and 50 dB) together

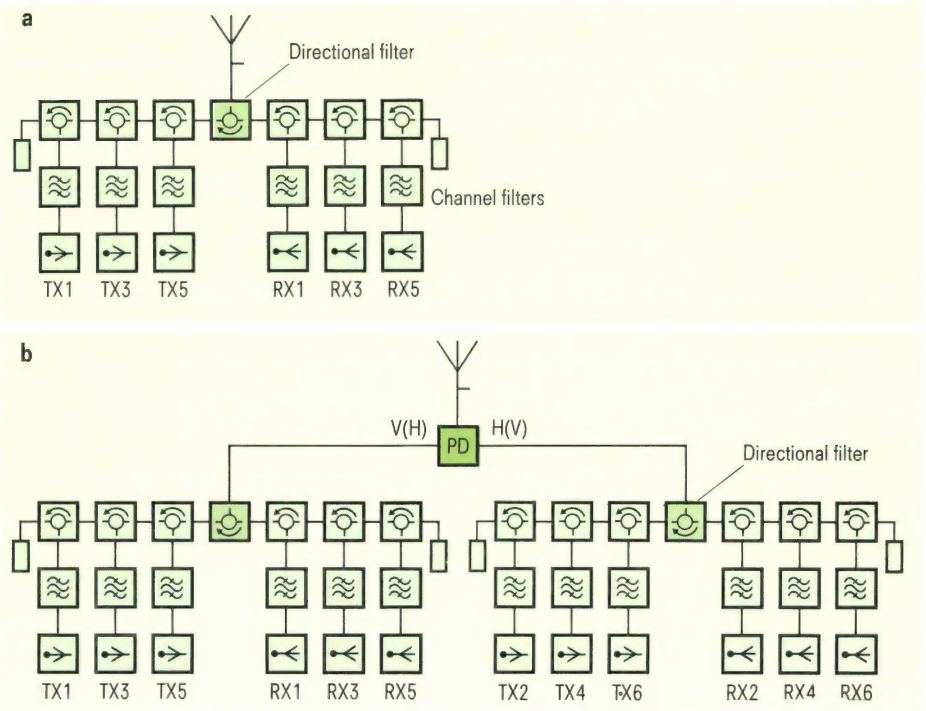
FM narrowband radio relay system	RF range f_{min} f_{max} (MHz)	Number of voice channels	Adjacent channel separation (MHz)	Service channel (kHz)	Radio pilot (kHz)	RMS frequency deviation (kHz)	Transmit power (W)	Noise figure (dB)	System value (dB)
FM 24-72/300	235 360	3–24/72	1.25/2.50	0.3 to 3.4	5	35/50	12 (15)	6	170/164 (161)/(155)
FM 24-72/400	345 470	3–24/72	1.25/2.50 (1.25)	0.3 to 3.4	5	35/50	6	6	167/161
FM 24-132/800	796 960	24/72/132	1.3/2.5/5.0	0.3 to 3.4	119/331/607	35/50/100	5 (1)	5	167/161/162
FM 300/1800	1700 1900	72/132/300	14	0.3 to 3.4	331/607/1499	50/100/200	1.5	7	154.5/155/ 115.4
FM 300/7200	7125 7425	132/300	7	0.3 to 3.4	607/1499	100/200	0.5	8	146/148
FM 300/7500	7425 7725	132/300	7	0.3 to 3.4	607/1499	100/200	0.5	8	149/148
FM 24-132/7200	7125 7425	12 24 72 132	0.25 0.5 3.5 7.0	0.3 to 3.4	5 5 5 607	35 35 50 100	0.5	9	153.5 153 147 148

Table 3 FM narrowband radio relay systems for medium-haul and special-purpose networks



FDM Frequency-division multiplex baseband
G Generator
M Test output
PIL Pilot equipment
RF Radio frequency
RS Remote supervision

Fig. 6 Family of FM narrowband systems, principle of single operation



H Horizontal polarization
PD Polarization diplexer
RX Receiver
TX Transmitter
V Vertical polarization

Fig. 7 Functional diagram for the connection of transmitters and receivers via channel branching filter chains, directional filters and diplexer to an antenna
a Three RF channel pairs on one antenna **b Six RF channel pairs on one antenna**

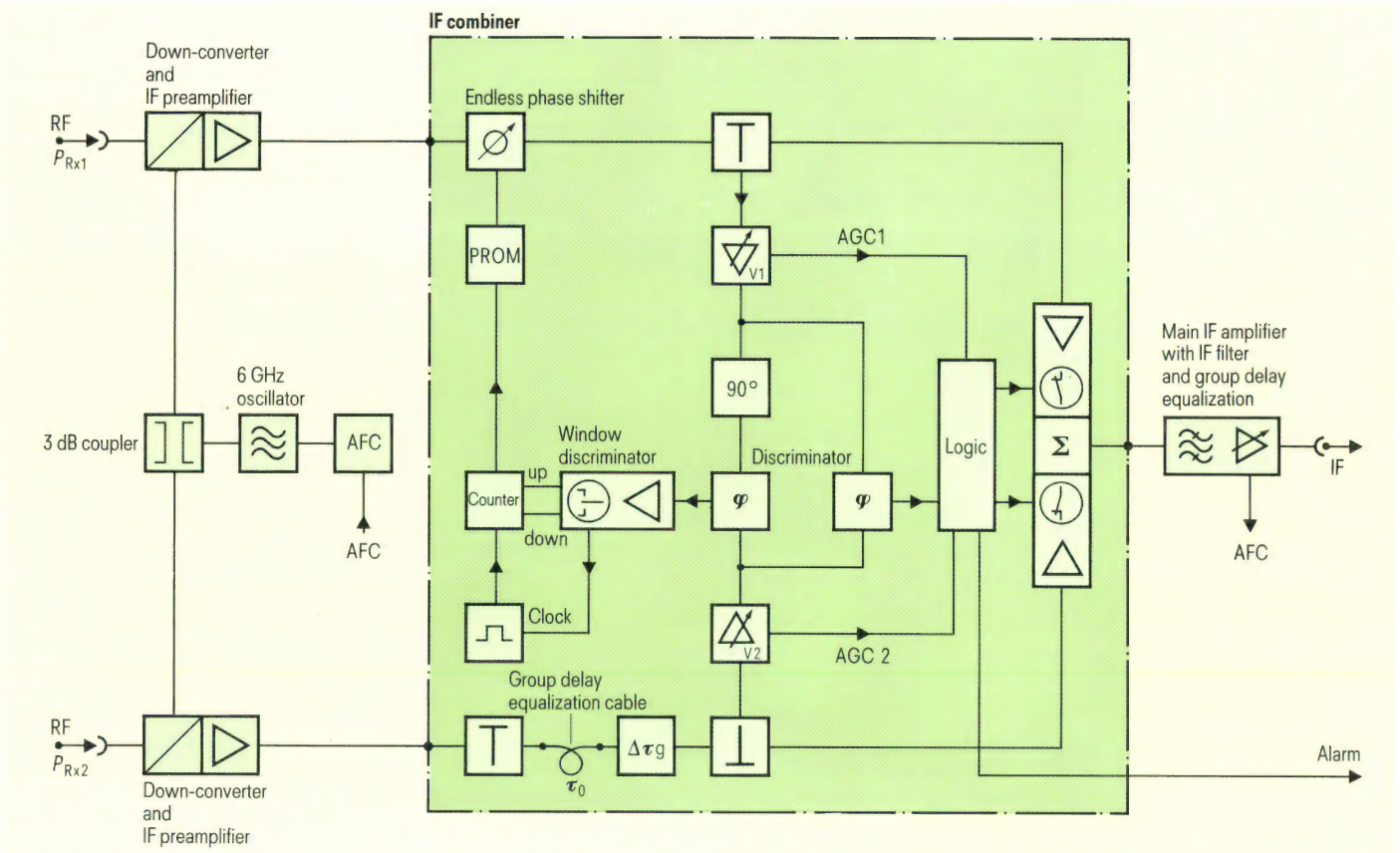
with very low insertion loss (0.05 dB) have been developed in extremely compact form for these applications [14]. A diplexer of this type is already in operation in the Deutsche Bundespost network for the GHZ bands, 2.2 and 3.5.

SIRAL® waveguides

The antenna feeder is assuming increasing importance in station construction, particularly at high frequencies. For this application, Siemens has developed a series of rectangular waveguides providing low attenuation and reflection (SIRAL® waveguide) [15]. This waveguide with its special cross section can be bent and twisted during installation without its characteristics being changed. For the frequency band above 10 GHz there are also low-attenuation versions available which can be operated above the upper cutoff frequency of the fundamental mode (overmoded) [16].

Channel branching filters and filter chains

In order to operate several radio relay transmitters and/or receivers on one



AFC Automatic frequency control
AGC Automatic gain control
IF Intermediate frequency
PROM Programmable read-only memory
RF Radio frequency

Fig. 8 Functional diagram of a space – diversity receiver with IF combiner

common antenna, each transmitter or receiver is assigned a channel branching filter. This comprises a circulator and a multi-section filter. Several such channel branching filters form a channel branching filter chain. The upper section of **Fig. 7** shows a typical arrangement with three channel branching filters in each of the transmit and receive branches connected to the antenna via a directional filter. The lower section shows two similar arrangements with a total of six transmitters and six receivers connected to the antenna via a polarization diplexer. Since the channel branching filters are an important factor in determining the transmission characteristics of the system, they and their characteristics have to be taken fully into account in planning the system approach. As a result, special channel branching filters have also been developed for all the analog radio relay systems presented [17].

Modem equipment

As previously mentioned, on wideband radio relay systems with IF through-connection the modulation and demodulation functions are performed in modem equipment separate from the radio units. The FM Mod 70/A and E family of modems was developed for the 70-MHz IF for the range of FM wideband systems. The FM 2700/140 modem equipment was developed for an IF of 140 MHz for the FM 2700/6700 wideband system. While this wideband system merely has to provide for the transmission of FDM signals with 2700 voice channels, the demands imposed on the 70-MHz family of modems are more varied. In order to meet the requirements of 70-MHz applications, versions for 300, 600, 960 and 1800 voice channels for FDM transmission have been developed together with three further versions for the transmission of TV signals together with one, two or four additional sound programs [18].

Data-above-baseband modems (DAB)

Siemens has developed special modems to utilize the frequency range available above the baseband for high-grade transmission of digital signals. These modems employ a quadrature-amplitude modulation (QAM) modulated auxiliary carrier (7.232 MHz for 960 voice channels and 10.304 MHz for 1800 voice channels) to transmit a 2.048-Mbit/s digital signal in addition to the FDM or TV signal [19]. In TV operation, this facility is employed for transmitting sound programs (sound broadcasting or television), for which purpose a PCM sound channel system is available for five stereophonic sound programs [20, 21].

Service channel and ancillary equipment for supervision and maintenance

For controlling and supervising the operation of analog radio relay networks, there is a wide range of ancillary equipment, such as service channel units, supervision equipments and units for inserting and removing additional FDM signals in the baseband. These ancillary facilities obviate the need to provide dedicated radio relay links for transmitting such signals and thus contribute to the cost-effectiveness of analog radio relay networks [22].

Protection switching, diversity operation; program switching equipment

A series of frequency-diversity and space-diversity equipments has been developed for protection against anomalies in atmospheric propagation conditions (e.g. multipath fading) which may restrict the availability of radio relay links. For frequency diversity there are (1 + 1) protection switching facilities (for hot standby also) as well as (N + 1) and (N + 2) protection switching facilities. They are available for switching at both the intermediate and baseband frequencies [23, 24].

For space-diversity applications there are IF combiners available with special receivers (e.g. for 2.1 and 6.2 GHz). These receivers combine the RF signals, obtained from two antennas at different heights, in the correct phase at IF. As illustrated in **Fig. 8**, an endless phase shifter in the signal path is controlled in such a way that the two signals are in phase at the summing point. The use of these IF combiners can produce a considerable improvement in the availability of critical hops, particularly over water or in desert areas.

Program switching facilities were developed as a derivative of the previously mentioned protection switching systems. They are used in TV transmission to switch programs, change directions, transfer the signal from studio to studio, establish test circuits etc. via controllable IF distributors [23].

Power supplies

In addition to a complete range of power supplies for the radio and ancillary equipment, there are also station power supplies, battery stations and self-contained power supply facilities available from development and project engineering activities of Siemens.

Summary

This review of Siemens analog radio relay systems demonstrates that a complete product range backed up by a larger number of necessary ancillary facilities and components has been created to meet all the requirements and conditions encountered in analog radio relay networks. This applies not only to the supply of sophisticated equipment, but also to the construction of turnkey radio relay networks, an area in which Siemens has achieved a number of significant successes in recent years.

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Hermann Barth, Theodor Bayer and Joachim Simon

Protection and Program Switching Equipment for Analog Radio Relay Links and Networks

The availability of radio relay links is affected not only by the propagation conditions on the hop, but also by the general availability of the radio relay equipment and its associated power supplies. By providing a standby circuit (another frequency or another path), automatic protection switching equipment makes a vital contribution to increasing the overall availability of radio relay links. In addition, program switching equipment is used in radio relay networks – e.g. for TV program distribution – in order to be able to switch the unidirectional routes in accordance with the programmed schedule. These distribution networks can in turn be protected by special network protection switching equipment.

For analog radio relay links and networks, a versatile, modular range of equipment for automatic protection and program switching has been developed, the basic components of which will be described in this article.

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Protection switching equipment

Virtually all radio relay links nowadays employ protection switching equipment. Transmission faults in one of *N* operating channels (OC) initiate automatic switchover from the disturbed signal path to an operable standby channel (STC). In special cases, two standby channels are provided for a multi-channel radio relay link.

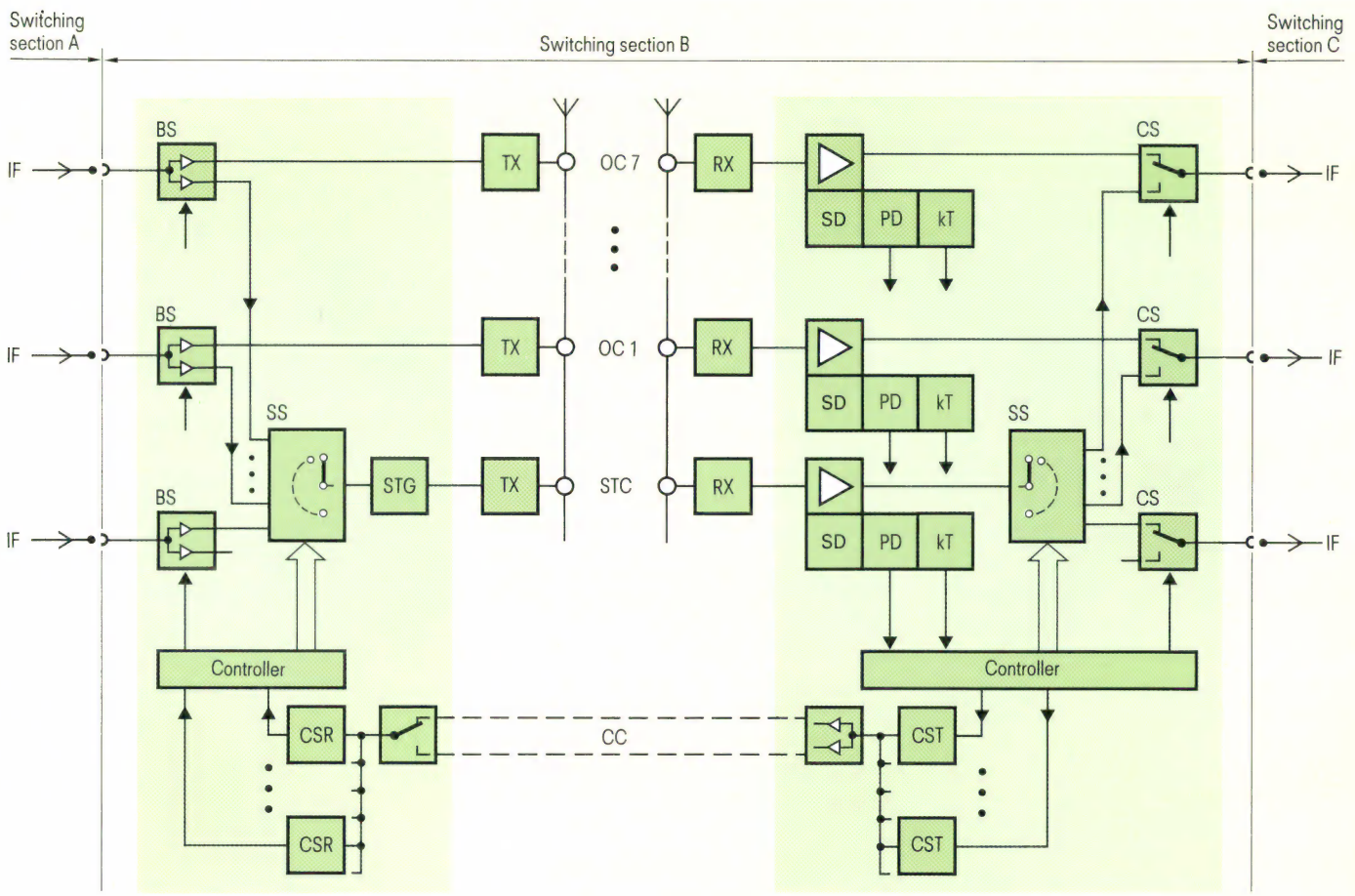
Equipment faults produce transmission disturbances at unpredictable times. Multipath fading on the hop degrades transmission quality to the point of signal loss. Taken as a whole, the resultant unavailability times can considerably exceed CCIR Recommendation 557. Using standby channels or standby equipment and the associated automatic switching facility as an effective means of increasing service reliability, it is possible to achieve the short outage times currently required at reasonable cost.

This approach relieves operating personnel of the need to replace defective units immediately and allows repairs to be carried out at a convenient time. It also allows more time to reach the site of the fault, so that a repair depot can serve a larger network than previously.

Manual protection switching by the maintenance staff during working hours allows routine quality checks to be performed without impairing transmission. This enables faults to be detected before they cause an outage, i.e. the quality of a link can be maintained at a high level.

Switching system requirements

When the protection switching system was at the concept stage, a list of



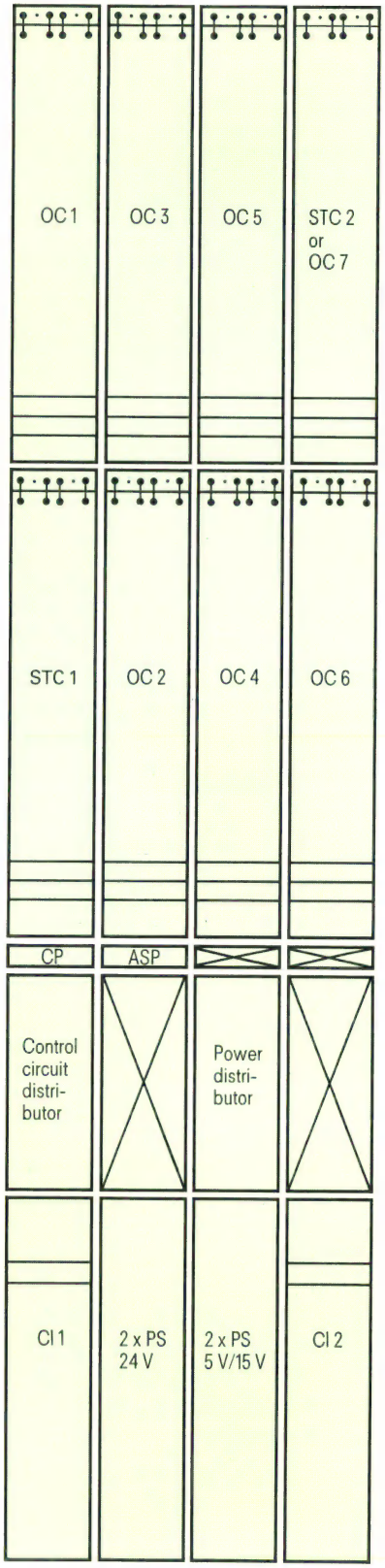
BS Branching switch
CC Control signal channel
CS Changeover switch
CSR Control signal receiver
CST Control signal transmitter
IF Intermediate frequency
kT Noise detector
OC Operating channel
PD Pilot detector
RX RF receiver
SD Supervision demodulator
SS Signal selector
STC Standby channel
STG IF standby generator
TX RF transmitter

Fig. 1 Functional diagram of the IF version of an (N+1) switching system (terminal stations shown for one direction)

requirements was drawn up, based on the above considerations and on the experience gained with equipment currently in operation. Some of the main requirements are:

- The switching equipment must be able to interoperate with a large number of extremely diverse radio relay systems without causing interfacing problems.
- It must be possible to assign standby channels to operating channels carrying different baseband signals, e.g. TV video or telephony.
- The switching facilities looped into the transmission path must introduce no insertion loss, so that freedom of station design is not restricted. Nor must they cause appreciable degradation of the wanted signals.
- The equipment must be suitable for switching multiplexed signals containing 300 to 2700 voice circuits at the 70 or 140 MHz intermediate frequency (IF) or at baseband (BB) frequency.
- Unprotected transmission branches must contain as few active components as possible, i.e. the availability of the circuit to be protected must be affected as little as possible by the switching equipment.
- Decentralization of the various functional units and modularization of the overall design must allow the protection switching equipment to be expanded channel by channel.
- Even when the radio relay channels are severely disturbed, the switching criteria must consist of unambiguous yes-no statements.
- The logic circuit must not transmit incorrect or ambiguous switching commands to the switching elements even in complicated network configurations. There must be provision for overriding the automatic equipment, either manually or via remote control, in order to initiate selective switching for maintenance or route expansion.
- The switching elements must provide short switching times and minimal intrinsic distortion.

These requirements provided the basis on which fully-automatic style 7R switching systems [1] have been developed. The modular design with plug-in functional units ensures that the maximum requirements of a (6+2) arrangement can be met as readily as those of (1+1) or (2+1) configurations, without



ASP Alarm signaling panel
CI Central inset
CP Control panel
OC Operating channel inset
PS Power supply
STC Standby channel inset

Fig. 2 Baseband (BB) and intermediate frequency (IF) protection switching equipment (N+2) in style 7R, configured for six operating and two standby channels

it being necessary for links with only a small number of radio frequency (RF) channels to be provided with facilities only required on subsequent expansion.

Operating principle of line protection switching equipment

Fig. 1 shows the basic electrical design of (*N*+1) protection switching equipment. On conversion to (*N*+2) operation, the transmit-end branching switches have a third output and the receive-end changeover switches a third input, which provide access to the second standby channel.

Each signal path in the switching section is monitored for continuity using a radio relay pilot. Quality is monitored in a dedicated noise channel at the pilot frequency. For this purpose, each channel is provided with supervision circuits which transmit a fault criterion to the controller if certain selectable thresholds are exceeded. The controller decides whether it is possible to switch over. If all the switching conditions detectable at the receive end are satisfied, this is communicated to the transmit end of the switching section via a (1+1)-protected control signal channel. Normally, service channels of the radio relay links to be protected are used for this purpose. The transmit-end control circuit bridges the standby channel to the disturbed operating channel. At the receive end, the standby channel detection circuit detects this and informs the control circuit, which in turn initiates protection switching at the receive end as well. The actual transfer time of the switches is only a few microseconds, whereas the overall time taken by the process described, i.e. the operate time, is 30 to 50 ms, depending on the type of fault.

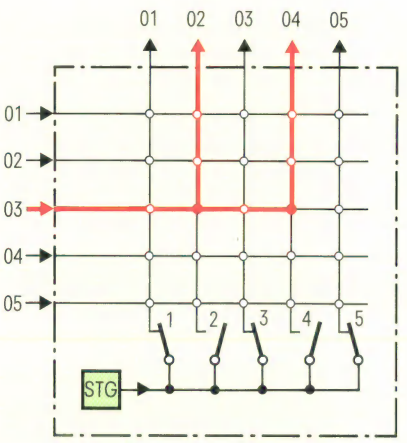
With (1+1) protection switching equipment, the two channels are continuously bridged at the transmit end. As there is no need for verification to be sent back to the transmit end, the operate time is reduced to approximately the time taken to detect the switching criteria.

Design of protection switching systems

(N+2) switching system

The units for this system can be used universally for (*N*+2) and (*N*+1) protection switching. If required, the

Fig. 3 (N+1) inset with integral radio relay modem



STG IF standby generator

Fig. 4 Schematic of a crossbar distributor for IF signals; circuit 03 is through-connected to circuits, 02 and 04

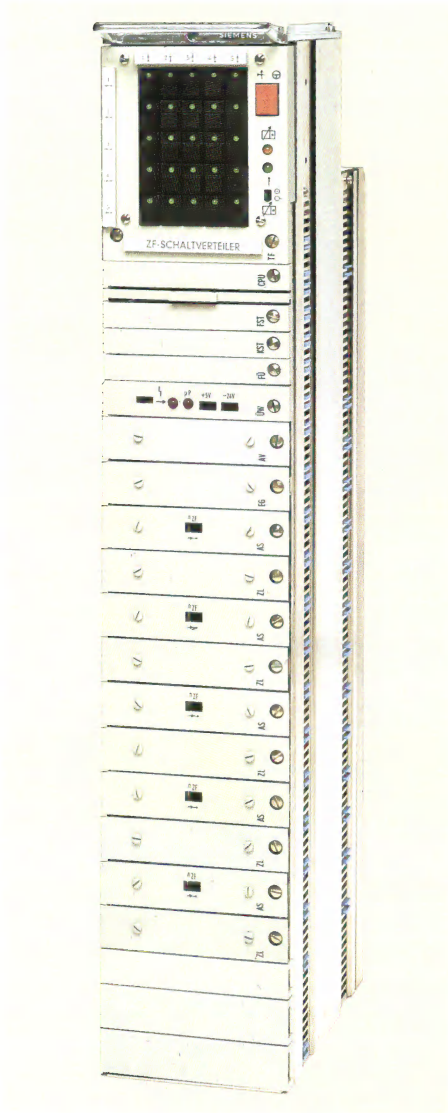
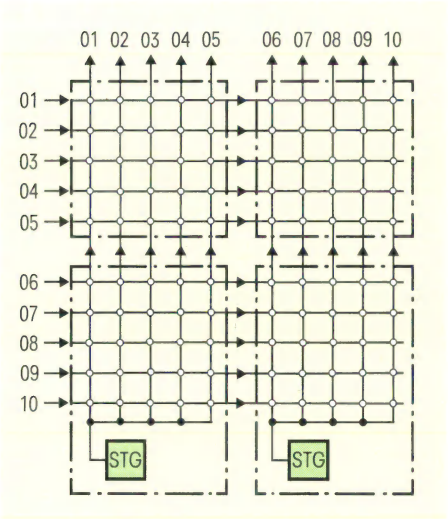


Fig. 5 IF switching distributor inset 5/5 for five incoming and five outgoing circuits



STG IF standby generator

Fig. 6 Basic circuit diagram of a 10/10 IF switching distributor for ten incoming and ten outgoing circuits

switching facilities can operate in the analog baseband, which may include a mixture of TV and FDM signals, or in the frequency-modulated IF band of 70 or 140 MHz.

The functional units required for each RF channel, such as the supervision units, controller, switch, control transmitter and control receiver, are accommodated in a 600 mm high type I style 7R inset, whereas the common equipment, e.g. the signal selectors in **Fig. 1**, are contained in an additional central inset. A (6+2) switching system, for instance, requires six operating channel insets, two standby channel insets and two additional central insets. The power supply is always of redundant design (**Fig. 2**).

If a partially equipped radio relay link requires a further operating channel, it is merely necessary to provide an additional operating channel inset. This can be done without interrupting the operation of the existing equipment.

A series of supervision and switch modules with identical electrical and mechanical interfaces has been developed for the different modes of 70 or 140 MHz IF or baseband switching. The equipment can be readily adapted to the particular mode required by replacing these plug-in modules. The logic circuit, control signal supervision modules, power supply section and channel supervision modules are identical for all the possible modes.

(N+1) switching system

The 600 mm high insets of this system accommodate the baseband (BB) switching modules of the (*N*+2) system together with the modulation units of the analog radio relay systems [2] (**Fig. 3**). The FM modulator and the FM demodulator both contain their own power supplies which are connected in parallel to supply the switching facilities on a redundant basis. Each RF channel therefore requires only one inset, containing switches, supervision modules, modem and power supply. The system is controlled by a central control inset with microprocessor logic [3]. This inset can be adapted to suit the capacity provided. In addition to the microprocessor, power supply and channel interface modules, it also contains a central display showing the current status of the system as well as keys for entering manual switching commands and assigning priority. It additionally incorporates the (1+1) protection switching equipment for the control signal link.

The units of this system provide an extremely economical (*N*+1) protection switching arrangement offering scope for easy expansion.

Equipment variants for (1+1) operation

On individual routes not intended for expansion into multichannel links, (1+1) switching facilities have been established using the above switch and supervision modules.

A (1+1) BB switching inset contains the transmit- and receive-end switching facilities for one operating channel and one standby channel. By replacing the "pilot generator" and "pilot receiver" units, this inset can be readily adapted to baseband capacities from 300 to 2700 voice circuits. The noise monitor optionally employs a fixed switching threshold – as with (*N*+2) line switching – or a floating threshold. This means that a difference in signal-to-noise ratio of some 4 dB causes traffic to be transferred to the better channel. In addition to the noise criterion, transfers are also initiated in response to pilot failure indications.

The 600 mm high (1+1) BB switching insets with integral modem are an extremely compact combination of transmit-end and receive-end switching equipment, each containing two modulators or two demodulators. The switches are controlled, as for baseband switching, by pilot and noise criteria; here too, the user has the option of a fixed or floating noise threshold for diversity operation. There are also (1+1) protection switching insets available for the 70 and 140 MHz IFs, which are likewise equipped to provide fixed or floating noise thresholds.

Transmission characteristics

In the above equipment variants of this modular system, the same switching and supervision modules are used for the same frequency bands (BB, IF 70 MHz, IF 140 MHz). Consequently, the transmission characteristics are also the same. **Table 1** lists some typical specifications.

BB switching (transmit or receive end, typical values)	
Transmit- or receive-end insertion loss	approx. 0 dB
Return loss up to 13 MHz	≥30 dB
Isolation between two channels	≥90 dB
Attenuation distortion (50 kHz to 13 MHz)	≤0.2 dB
Insertion noise in highest-frequency FDM channel	≤5 pWOp
IF switching (transmit or receive end, typical values)	
Input voltage (rms value)	0.3 V
Output voltage (rms value)	0.5 V
Isolation between two channels	≥85 dB
Attenuation distortion	≤0.2 dB
Group delay distortion	≤0.2 ns
Insertion noise for transmit or receive end	≤5 pWOp
Switching times	
Transfer time	≤10 µs
Operate time	approx. 30 ms

BB Baseband
FDM Frequency-division multiplex
IF Intermediate frequency

Table 1 Specifications of the modular system for automatic switching of radio relay links

Intermediate frequency	70 MHz
Standby generator	
intermediate frequency	70 MHz
pilot frequency	8.5 MHz
sound carrier frequency	7.5 MHz
IF input voltage (rms value)	0.3 V
IF output voltage (rms value)	0.5 V
Characteristic impedance at input and output	75 Ω unbal.
Return loss (70 MHz ± 12 MHz)	≥28 dB
Attenuation distortion (70 MHz ± 12 MHz)	≤0.5 dB*
Group delay distortion (70 MHz ± 12 MHz)	≤1 ns*
Differential gain	≤0.5%*
Differential phase	≤0.5°*
Crosstalk attenuation	≥80 dB
Transfer time	≤10 µs
Battery voltage	40 to 75 V
Power consumption from battery per 5/5 switching inset	about 30 W
Operating voltages	+5 V; −24 V

* depending on capacity stage

Table 2 Specifications of the intermediate frequency (IF) switching distributor

Program switching equipment

Switching is frequently required at nodes in radio relay networks used for TV transmission. For example, programs have to be switched several times a day on links from studios to transmitters, from studios to studios, for inserting test cards and setting up test circuits [4]. The common feature of all switching operations is that an incoming signal from a radio relay link must be switched to one or more outgoing links. Signals are through-connected at IF in order to avoid demodulation and modulation distortion. The following paragraphs describe the IF switching distributors used for this purpose.

Operating principle

The basic unit of the IF switching distributor contains electronic switches in the form of a matrix of five rows and five columns configured on the crossbar distributor principle. The basic layout is shown in **Fig. 4**. In the example illustrated, the IF signal of incoming circuit, 03, is switched to outgoing circuits, 02 and 04. Microprocessor logic circuitry ensures that the signal of another incoming circuit is not switched to one of these outputs simultaneously. In order to ensure that the unassigned outgoing circuits are monitored, the microprocessor logic connects the pilot-modulated signal of an IF standby generator to these circuits.

Design of the program switching equipment

The style 7R, type I, IF switching distributor inset shown in **Fig. 5** contains the electronic switches and amplifiers for five inputs and five outputs, i.e. switching facilities for 25 nodes. The 600 mm high inset additionally accommodates the microprocessor controller as well as the display and key panel. Each illuminated key represents a switching node whose state is indicated by an LED. Capacity can be expanded by connecting additional switching distributor insets to expansion outputs. An IF switching distributor for $2 \times 5 = 10$ incoming circuits and $2 \times 5 = 10$ outgoing circuits therefore consists of four insets. These insets are likewise configured on the crossbar principle (**Fig. 6**) such that the illuminated keys of each inset represent one of the $10 \times 10 = 100$ nodes. It can be seen that the signals of incoming circuits, 06 to 10, have to pass through the switches of three insets on their way to outgoing circuits, 06 to 10. Owing to the very slight but unavoidable degradation of an IF signal as it passes through the switches, the maximum system capacity is limited to 20 incoming and 20 outgoing circuits. If it is not necessary for every input signal to reach all the outputs, a partially equipped configuration is possible. For overall control of the electronic switches in the different insets, the microprocessor controllers of the insets are interconnected via bus circuits.

A wanted connection is switched in two stages. First, the nodes are primed for switching by actuation of their illuminated keys. They are then through-connected by a common execute command. Contradictory commands are disregarded by the controller. The switching status can also be controlled remotely; it

is similarly possible to connect a remotely located control desk. Two-stage switching ensures that operator error is virtually eliminated and that the actual switching action only takes about 5 µs, irrespective of the speed of the selection procedure.

Table 2 lists electrical specifications for a program switching equipment with 10 incoming and 10 outgoing circuits.

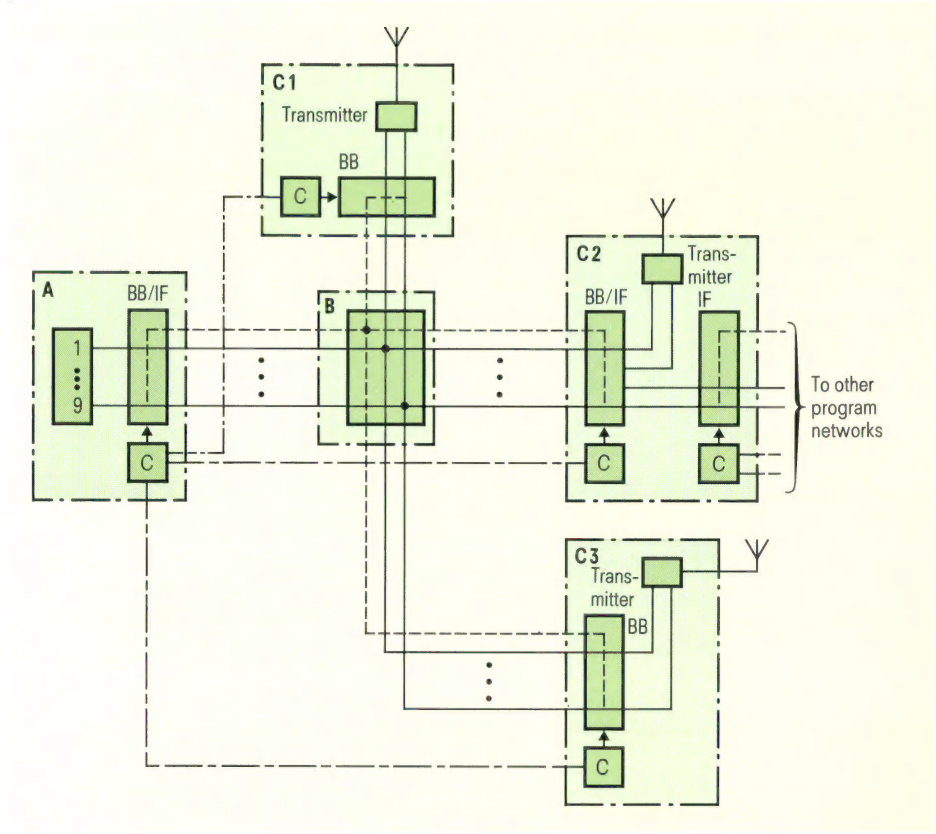
Network protection switching

PTTs use a radial pattern of radio relay links to transmit programs to the TV transmitters of an area. For this network of unidirectional links, a special protection switching system has been developed whose switching and detection modules are based on the $(N+2)$ protection switching system. This program network protection switching system (**Fig. 7**) uses a standby channel following all the branches of the program circuit network to protect the program circuits for up to nine simultaneously available TV programs. A central transmit station (hub station) can be assigned up to 12 receive stations with their TV transmitters. A network spur can itself become a hub to its own program network.

TV programs can be handled in the hub station at IF via program switching equipments or at baseband (video) frequency in the case of signals coming from a local studio. Consequently, the network protection switching equipment must be able to receive, retransmit and switch both BB and IF signals. The sound signals transmitted in parallel with the TV programs as frequency modulated or quadrature amplitude modulated subcarriers [5] are protected by a sound protection switching equipment operating in parallel. It is controlled simultaneously by the switching criteria. Protection switching of the TV sound signals occurs at audio frequency.

Operating principle of network protection switching

If a program circuit is disturbed – indicated by loss of pilot or sound carrier at a receive station – traffic is automatically transferred to the standby channel. The operating channel disturbance detected at the receive station is notified to the hub controller by a message transmitted via a control signal circuit operating independently of the program network.



Operating channels 1 to 9
Standby channel
Branch
Control signal circuit
IF and/or BB switch

A	Regional switching and feeding station (hub)
B	Branching station
BB	Baseband signal
C	Controller
C1, C3	Receive stations
C2	Receive station with feed to the hub station of another program network
IF	Intermediate frequency signal

Fig. 7 Part of a program network

This central controller evaluates the indications from all the receive station controllers, initiates bridging of the standby channel (if available) to the disturbed operating channel and transmits a verification message to all the terminal stations. It is, however, only the disturbed receive station that executes a switchover on receipt of the verification message.

In the receive stations, the signals are switched after passing through the demodulators and sound attachments. Consequently, all the program network equipment is covered by the protection switching system.

Protection switching occurs not only automatically but can also be initiated manually for maintenance purposes. Manual switching is initiated via keys on the control insets of the receive stations and of the central transmit station as well as via supervisory control facilities. Manually initiated automatic system testing is possible. An automatic transfer with the system fully equipped takes up to 360 ms, a manual transfer about 5 µs.

Equipment design

When the system is fully equipped, the switching facilities at the hub station are concentrated in two 600 mm high style 7R type I insets. One inset accommodates the modules of six operating channels, and an expansion inset accommodates those of three operating channels. At the receive stations, the switching facilities are arranged in two or three insets when the system is fully equipped, depending on whether switching must take place entirely at baseband or entirely at IF or whether a combination of the two is required. At both the hub and receive stations, the switching facilities for the sound signals are located in separate insets.

At branching stations (**Fig. 7**), the signals are branched on a permanent basis only. The branching modules required for this purpose are grouped in a 600 mm high inset for up to six channels. The control inset is very similar to the inset shown in [3]. It contains a microprocessor logic circuit, a central display with keys for entering manual instructions and interface modules for up to ten channels. Receive station control insets additionally contain a frequency-shift keying (FSK) modem for transmitting control messages. Each receive station requires an FSK modem at the hub station. The modems for up to six receive stations are accommodated in a separate 500 mm high inset, but are controlled by the control inset microprocessor.

The operating voltage for the insets described is provided on a decentralized basis. Each inset contains its own power supply. For the switching insets, the operating voltage is provided on a redundant basis.

Summary

The availability of analog radio relay links can be considerably enhanced by means of automatically operating protection switching equipment. A wide range of equipment has been developed for this application. The equipment can be configured to provide protection switching both at IF (70 and 140 MHz) and also at BB frequency, in which case the channels can contain either telephony or TV signals. Program switching equipment is available for rapid rerouting of TV program circuits for operational reasons. A switching matrix operating at IF (70 MHz) can be used to switch up to 20 incoming signals to any of 20 outgoing circuits.

As part of a modular system, the units used in the equipment described can be readily adapted to suit specific project requirements. Line protection switching is being developed to provide network protection switching with control at network level to increase the availability of the maximum number of links. A typical example of this is the supergroup protection switching system used in the Deutsche Bundespost network.

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Wolfgang Hecker, Klaus Peterknecht and Josef Scholz

Radio Relay Systems FM-TV/2200 and FM-TV/3500 for Television Program Transmission

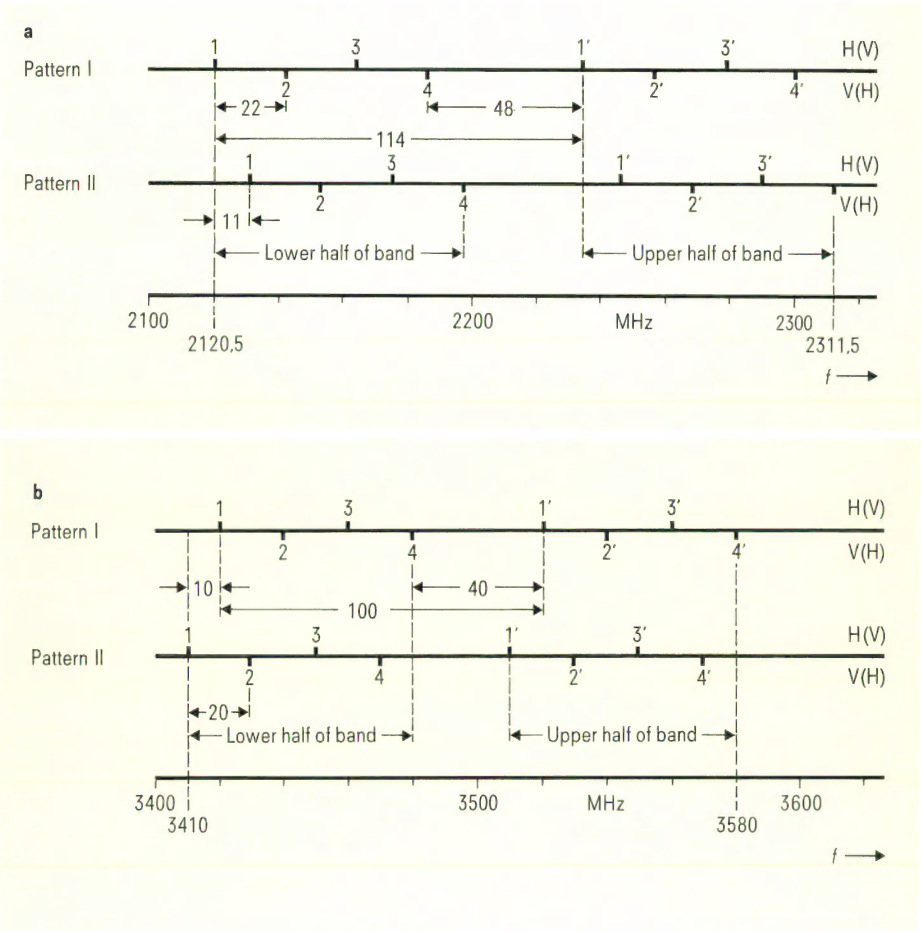
The desire for a wider variety of television and sound programs allied to the need to release existing radio-frequency (RF) bands (e.g. the 4-GHz band) for new services led to the development of two radio relay systems for the transmission bands 2.2 and 3.5 GHz. Each of these 200 MHz wide frequency bands enables up to four RF channel pairs – or a total of up to eight RF channel pairs on the two frequency bands using a system diplexer – to be operated in parallel on one antenna [1, 2].

The equipment presented in this article is compatible with existing analog systems as regards picture transmission and intermediate-frequency (IF) through-connection. The accompanying sound can be transmitted above the video band as a digital or analog signal depending on supplementary equipment. The system design also provides for analog transmission of a total of 960 voice channels.

The transmitters and receivers of both systems can be readily set to all RF channels without additional test equipment and without changing crystals (synthesizer). Although the two systems differ in certain respects electrically, they share the same mechanical dimensions both for the equipment insets and the rack structure.

RF channel arrangement

The RF channel arrangements for FM-TV/2200 (3500) shown in **Fig. 1** comprise two identical patterns displaced by half the RF channel separation, each with four RF channel pairs. Cochannel operation at a radio station requires isolation between antennas of better than 60 dB. Sidelobe isolation between 45 and 60 dB requires a change of frequency pattern. At a given station, all the transmit frequencies lie in one half of the band, the receive frequencies in the other half (lower or upper half of the band). The narrow RF channel separation of 22 (20) MHz provides highly efficient frequency utilization within the available bandwidth of 191 (170) MHz (based on the RF-channel center frequencies in each case). In both frequency bands, the pattern arrangements provide compatibility with the adjacent DRS 34/1900 and DRS 140/3900 digital systems.



H Horizontal polarization V Vertical polarization

Fig. 1 RF channel arrangements for the FM-TV/2200 (a) and FM-TV/3500 (b) radio relay systems

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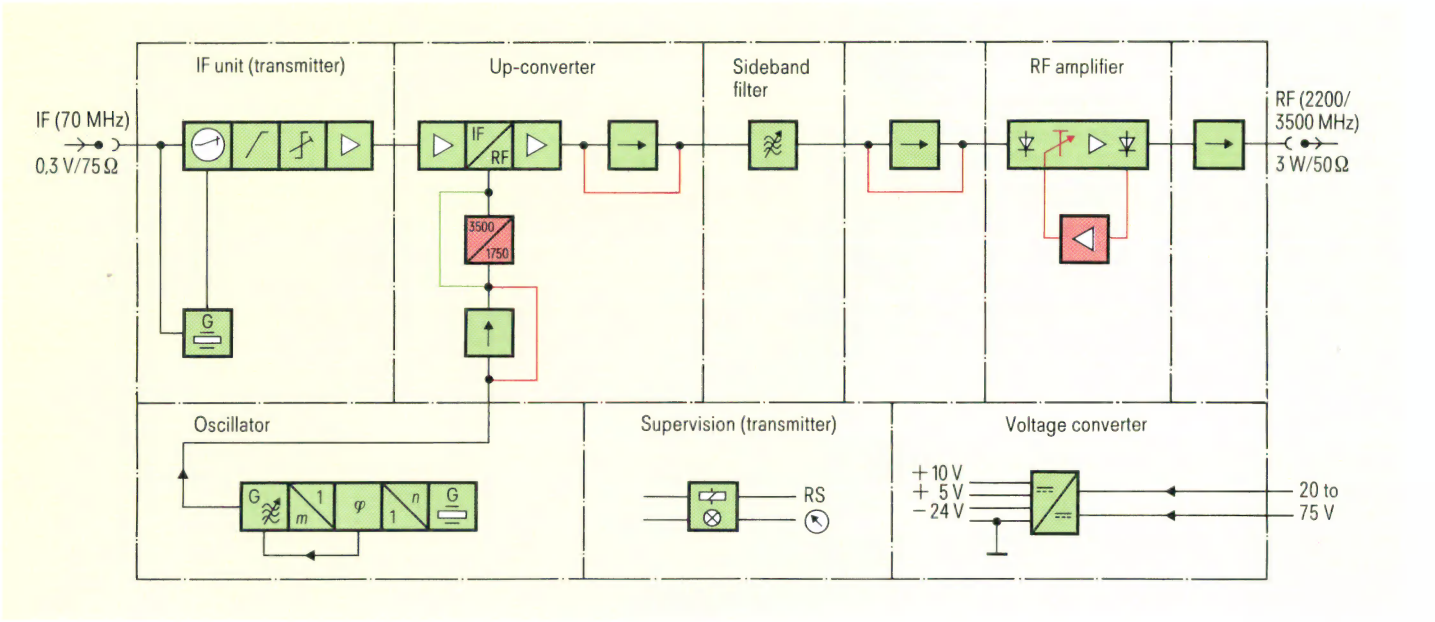


G Generator
φ Phase angle
IF Intermediate frequency
m, n Division factors
RF Radio frequency
RS Remote supervision

Fig. 2 Functional diagram of the FM-TV/2200 transmitter; additions for FM-TV/3500 are marked in red

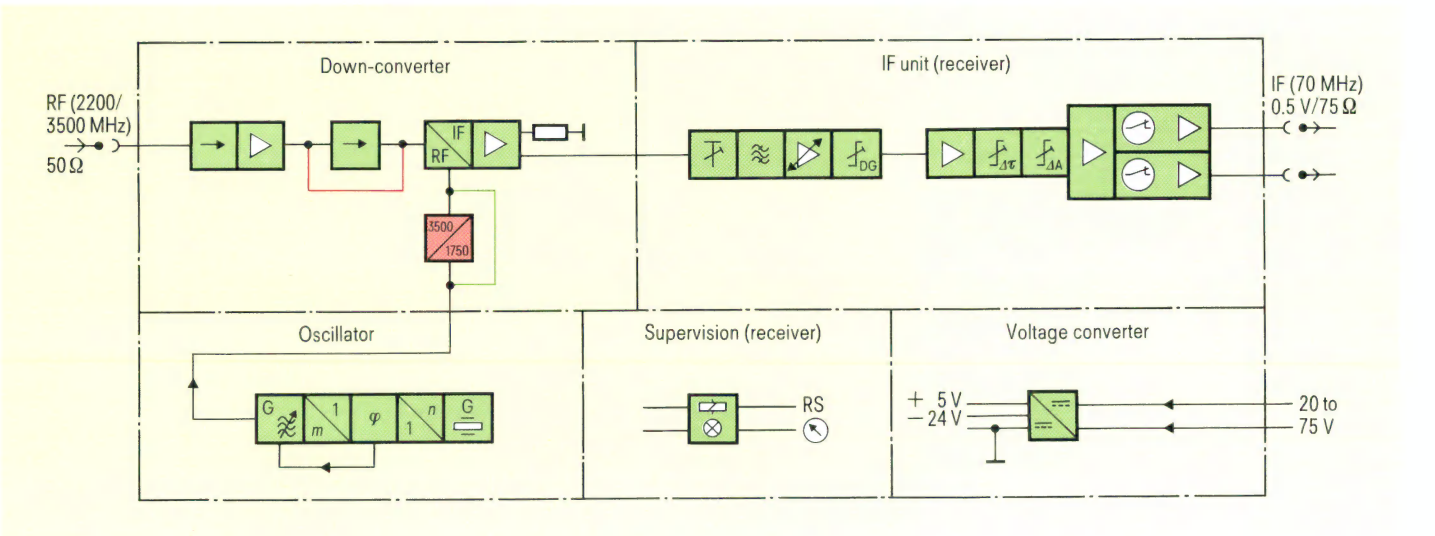
Transmit and receive equipment

The transmitter (**Fig. 2**) obtains the 70-MHz IF signal (0.3 V rms) from the modulator in terminal stations and from the associated receiver in repeater stations. This signal is monitored at the transmitter input. If the IF voltage falls below its nominal value, the signal input is automatically disconnected and a 70-MHz standby crystal generator is simultaneously connected to the transmitter input in order to maintain a carrier signal on the link.

The IF signal is fed to a limiter to remove the amplitude modulation (AM) components and then to a single-sideband up-converter, where it is translated to the RF band by being heterodyned with a carrier frequency. (The RF power is then raised by a gain-controlled amplifier to the level required for the final amplifier.) A tunable sideband filter increases the selectivity of the converter. On a change of frequency this filter is tuned to produce the maximum voltage at the input probe of the RF amplifier. This voltage is amplified and indicated on the associated meter as the tuning criterion.

In the *FM-TV/2200 system* the semiconductor RF amplifier operates in class C. Its output power is monitored with the aid of a probe and is then passed through an isolator.

The carrier frequency for the up-converter is produced by a transistor oscillator



G Generator
φ Phase angle
IF Intermediate frequency
m, n Division factors
RF Radio frequency
RS Remote supervision

Fig. 3 Functional diagram of the FM-TV/2200 receiver; additions for FM-TV/3500 are marked in red

whose frequency can be selected in steps of 250 kHz via a synthesizer. For this purpose, the oscillator frequency must be reduced via a programmable divider for the phase comparison, while the reference frequency derived from a crystal is produced by a fixed divider. A loss of lock results in the RF transmit signal being blocked.

On a change of frequency, the variable divider is programmed via switches according to the radio frequency required and the oscillator is set to the center of the lock range of the phase-locked loop by turning a drive accessible from the front panel. The appropriate indication appears on the previously mentioned meter.

In the receiver (**Fig. 3**), the RF signal from the channel branching filter undergoes low-noise preamplification before being translated back to the 70-MHz band in the single-sideband converter. The wideband RF preamplifier in conjunction with the single-sideband converter produces an improvement in noise figure. Additional selectivity is not required, since the image frequency is attenuated in the single-sideband converter by about 20 dB. The IF signal then passes through a five-section IF filter, a gain-controlled IF amplifier, active equalizers (for delay, differential gain and amplitude) and an IF splitter with two isolated, identical outputs. The second output allows, for instance, a TV program to be dropped at IF.

Both IF outputs are disabled electronically if the receive level falls below a certain selectable threshold (squelch) or if oscillator lock is lost. The transmit and receive oscillators are of identical design.

The transmitter and receiver each incorporate a supervision unit. Light-emitting diodes indicate any faults. The principal operating parameters can be selected with a switch for indication on a meter which can be connected via a plug to the supervision unit. The operating parameters of several equipment insets which may be located in different racks are indicated on a common meter. In addition, the supervision units incorporate switches and relay contacts required for extending the alarm signals to the remote supervision facility.

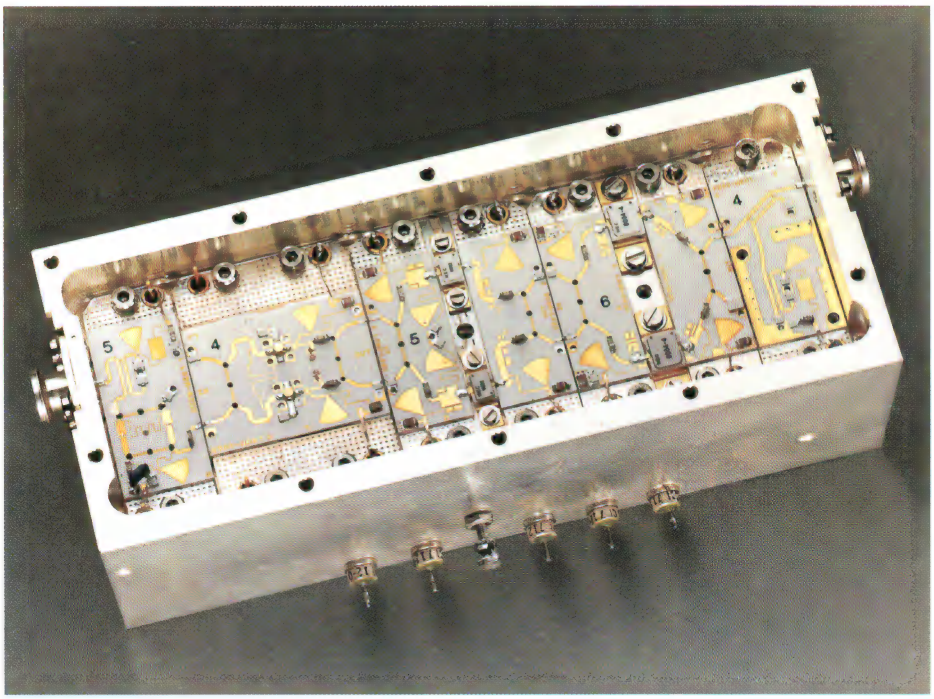


Fig. 4 Radio-frequency (RF) amplifier for the 3.5-GHz band

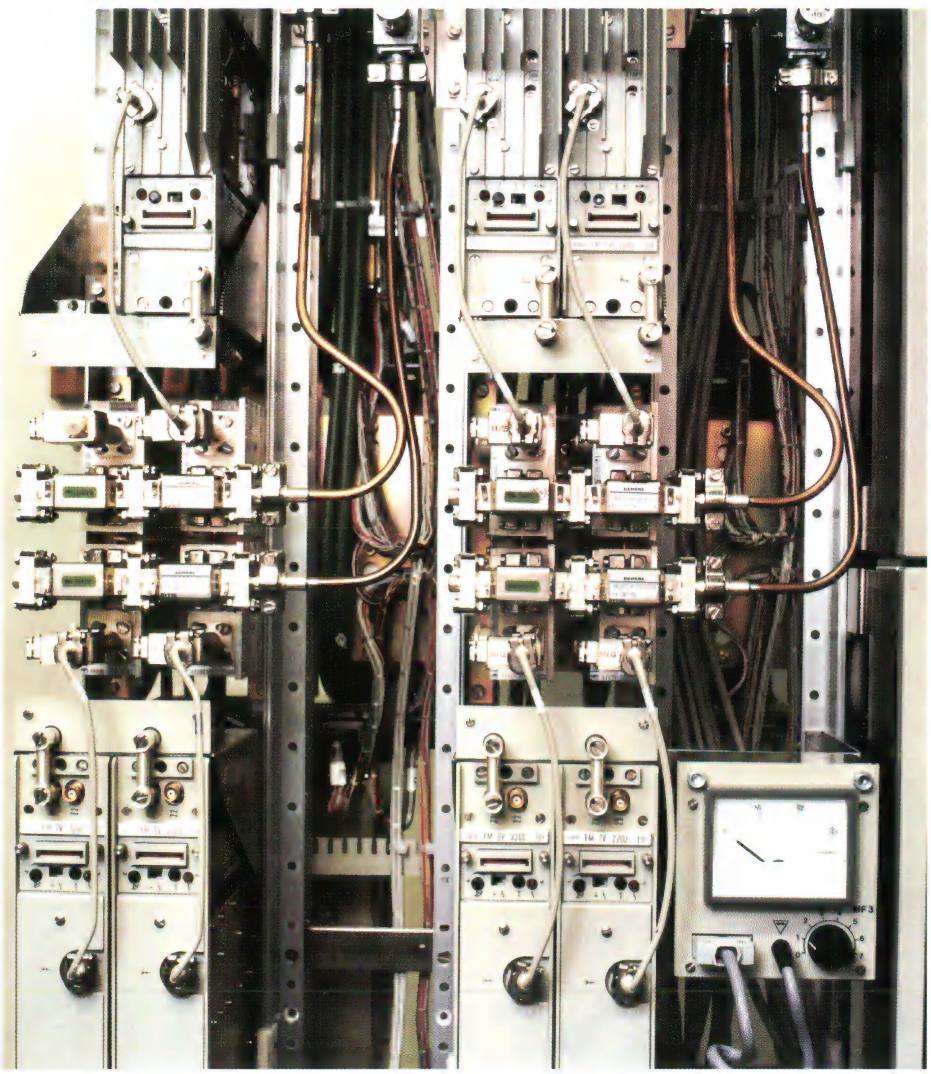


Fig. 5 Channel branching filter configuration of the FM-TV/2200 radio relay system for four RF channel pairs

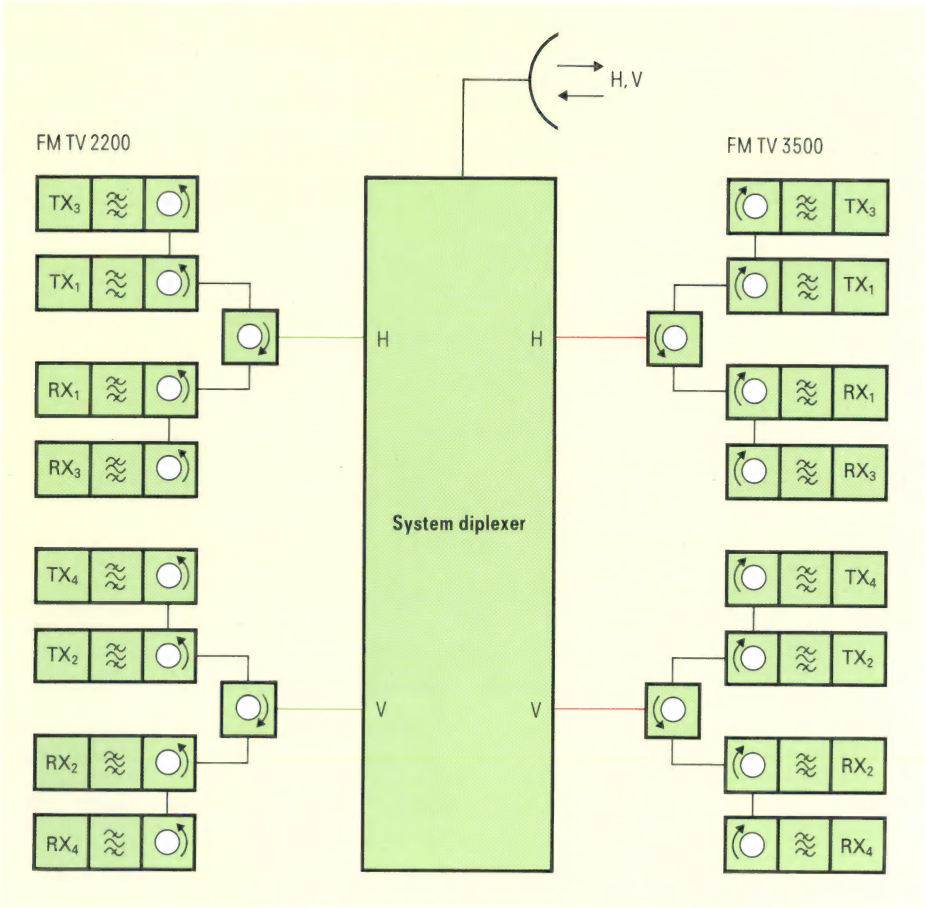


Fig. 6 System diplexer and channel branching filter circuits

Each transmitter and receiver incorporates its own low-loss voltage converter for converting the available supply (20 to 75 V) to the internal operating voltages (−24 and +5 V). In keeping with the modular approach, both systems employ modules which are largely identical. The *FM-TV/3500 system* differs from the *FM-TV/2200* (**table**) in the RF modules. The RF signals required for the conversion processes are derived from the master carrier supply by frequency doubling. The doubler circuits are mechanically integrated into the converters. As a result, the smallest programmable increment of the synthesizer is increased from 250 to 500 kHz referred to the radio frequency. The RF amplifier used in this system (**Fig. 4**) was implemented with GaAs field-effect transistors (FET) on ceramic substrates. It is subdivided into three amplifier sections operating in class A. Each of these sections is designed as a balanced amplifier where two transistors are coupled via hybrid circuits at the input and output so that the powers of the two transistors add. A controllable input attenuator provides automatic output power regulation, thus compensating level tolerances in the transmit signal path. A protective circuit is provided to protect the RF power stages against a variety of damaging electrical influences. The RF amplifier employs an operating voltage of +10 V and two auxiliary voltages of ±15 V required for the protective circuit.

The low-noise RF preamplifier in the down-converter is also a hybrid-coupled GaAs FET circuit on a ceramic substrate and incorporates an integrated isolator in the input [3]. In order to protect the receiver input against signals from sources other than radio relay, it is possible to insert an RF power limiter between the receive channel branching filter and the receiver.

Radio relay systems	FM-TV/2200	FM-TV/3500
Radio-frequency range	2.1 to 2.3 GHz	3.4 to 3.6 GHz
Minimum channel spacing	22 MHz	20 MHz
Transmit power	3 W	2 W
Receive noise figure	≤4 dB	≤4.5 dB
TV system value (CCIR Rec. 567)	156.8 dB	154.5 dB
Receive level range	(−22) −28 to −80 (−84) dBm	
Supply voltage	20 to 75 V	
Power consumption		
Transmitter	38 W	32 W
Receiver	12 W	12 W

Table Principal electrical specifications for the FM-TV/2200 and FM-TV/3500 radio relay systems

Channel branching filters and antenna system

The channel branching filters on the transmit side are used to provide combining of the transmit signals. On the receive side, they ensure correct assignment of the receive signals. They each comprise a six-section band-pass filter, a circulator and an equipment-side isolator. In the *FM-TV/3500 system*, the transmit channel branching filter does not incorporate an equipment-side isolator. Pairs of channel branching filters are combined as standard to form a channel branching filter chain terminated with a resistor. A transmit and a receive channel branching filter chain can be connected via coaxial lines incorporating directional couplers and low-pass filters and leading to a duplexing circulator. This circulator provides isolation between the transmit and receive paths and an adapter to the antenna feeder. **Fig. 5** shows the channel branching filter configuration for the FM-TV/2200 radio relay system.

The band-pass filters are designed with coaxial resonators and have a 3-dB bandwidth of 30 MHz. By slightly displacing the center frequency of one filter towards the frequency of the adjacent filter in the same channel branching filter chain it is possible to compensate the delay slope caused by reflection from

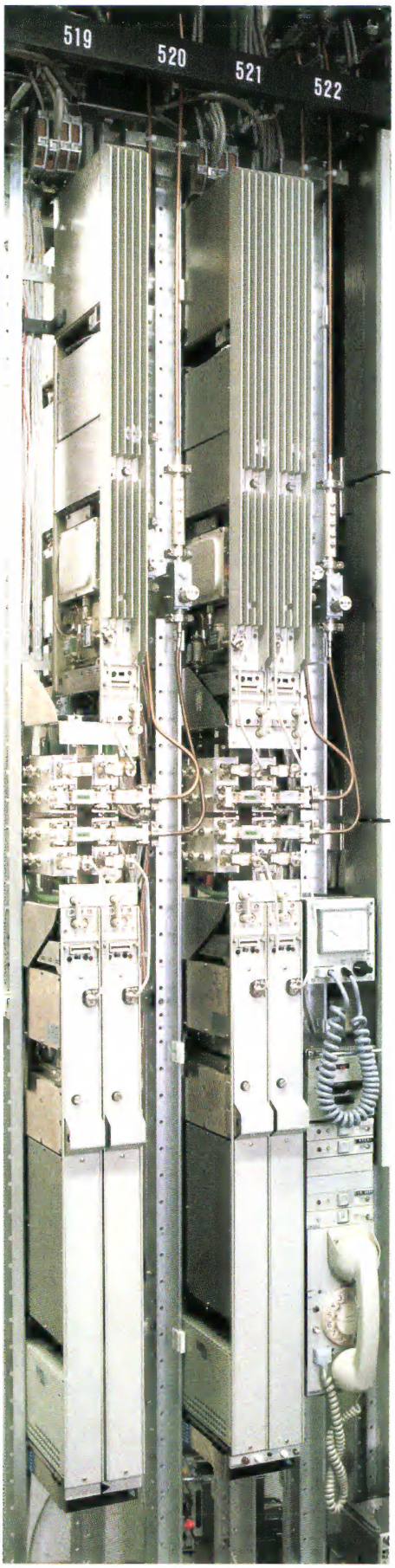


Fig. 7 Equipment configuration in the rack frame as illustrated by the FM-TV/2200 radio relay transmission system

the adjacent filter and thus obtain virtually the same delay distortion for all RF channels. The advantage of this is that the delay equalization in the receiver – disregarding tolerances – can be the same and receiver replacement will produce only small deviations in the group delay.

Shell-type antennas are provided for both systems. The primary radiator and polarization diplexer assembly housed in the antenna case determines the possible applications as being either for one of the two frequency bands (2.2 or 3.5 GHz) or for the space and cost-saving solution with integral system diplexer (**Fig. 6**), combining both frequency bands [2]. The antenna is fed via coaxial cables (2.2 GHz) or S40 SIRAL® waveguide (3.5 GHz).

Mechanical design

Transmitters and receivers (including the voltage converters) are mounted in an 800 mm high style 7R6 vertical inset [4]. A rack can accommodate two transmitters and two receivers as well as the associated channel branching filters between the radio sections (**Fig. 7**). An additional rack located on the right of the radio rack accommodates the lines incorporating the low-pass filter and directional coupler and connecting the channel branching filter chains to the duplexing circulator. It also contains the built-in meter, if provided.

The 121 mm wide, style 7R6 racks consist of two L-section uprights 2.60 m high. The radio units are inserted and secured in inset housings preinstalled in the rack. The wiring leads from the inset housings to a terminal panel mounted at the top of the rack, providing plug-in connections to the station wiring. The rack can also be used for other style 7R6 radio relay units.

Supplementary equipment

If required, the units of a radio relay system can be augmented by supplementary equipment.

The FM-TV/70A modem contains the modulating and demodulating equipment for translating a composite baseband (video and sound programs including the 8.5-MHz pilot) to and from the 70-MHz band. The sound program is transmitted at baseband frequency between the video and pilot signals. Instead of using conventional analog transmission with double frequency modulation (FM), a greater number of sound programs can be transmitted by the 2-Mbit/s data-above-baseband modem, DEG 2/7, meeting more exacting quality demands by transmitting a 2-Mbit/s signal by means of the DEG 2/7 data-above-baseband modem. This permits the transmission of, for instance, 5 (10) sound programs with a bandwidth of 15 (7) kHz each.

Baseband (BB) and intermediate-frequency (IF) protection switching equipment as well as supervisory control facilities are also available, if required. The equipment is operated from power adapters for 110/220/240 Vac supplies (47 to 63 Hz) or from floated batteries.

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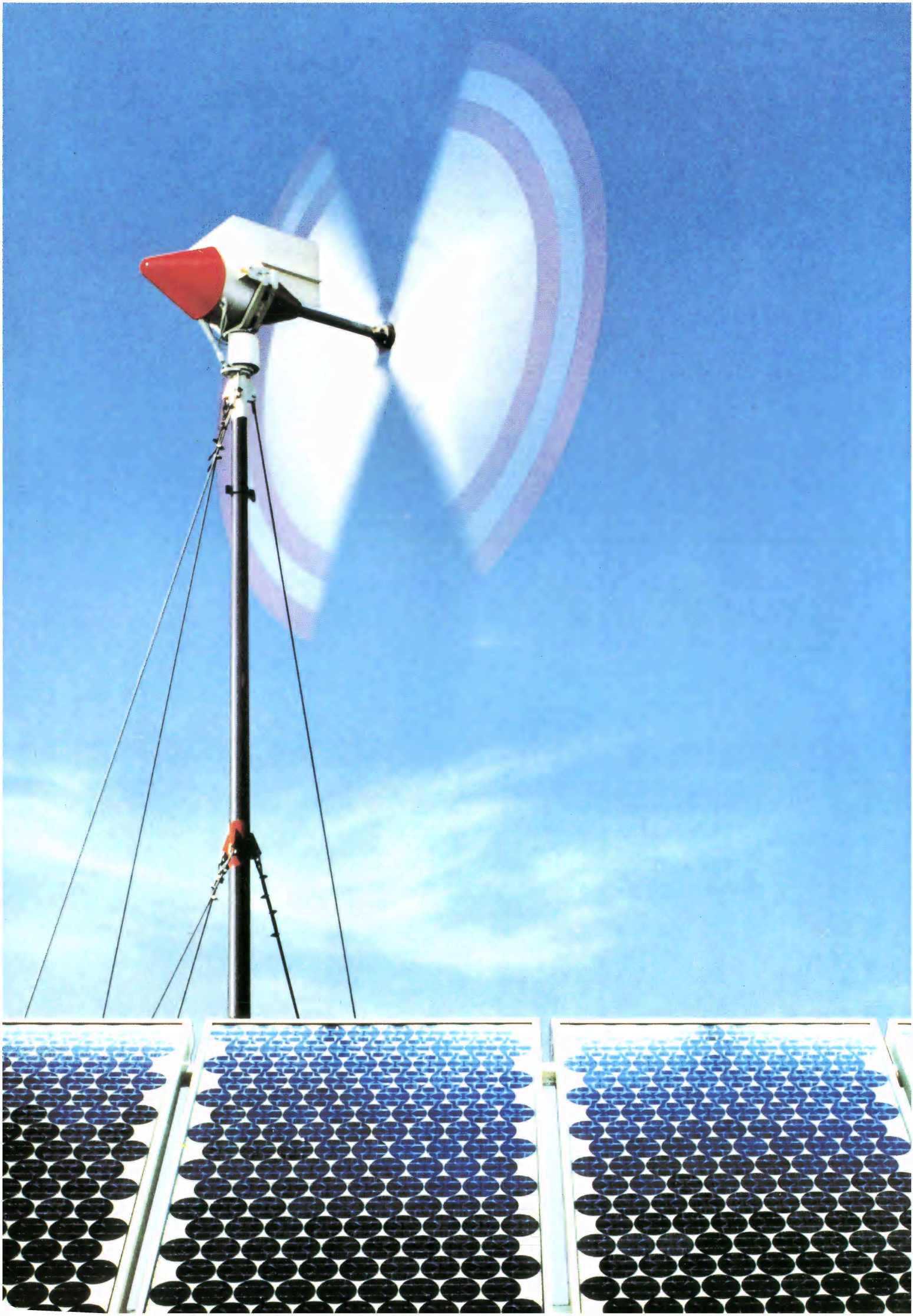

Peter Eichhorn, Klaus Kübler and Heinrich Pascher

Self-Contained Power Supply Systems

A problem often encountered in setting up radio relay transmission links is the lack of a commercial power supply network to power the repeater stations. In such situations it is necessary to provide a self-contained power supply adapted to conditions in the particular country. For stations with a high power requirement it is usual to employ conventional systems, i.e. dual or triple diesel power plants with rectifiers and batteries (*Fig. 1*). For stations where access is difficult, e.g. in mountainous or desert regions, or for low-power stations, however, increasing use is being made of solar and wind energy.

Fig. 1 Radio relay repeater station in the Sultanate of Oman with shelter-installed dual diesel plant

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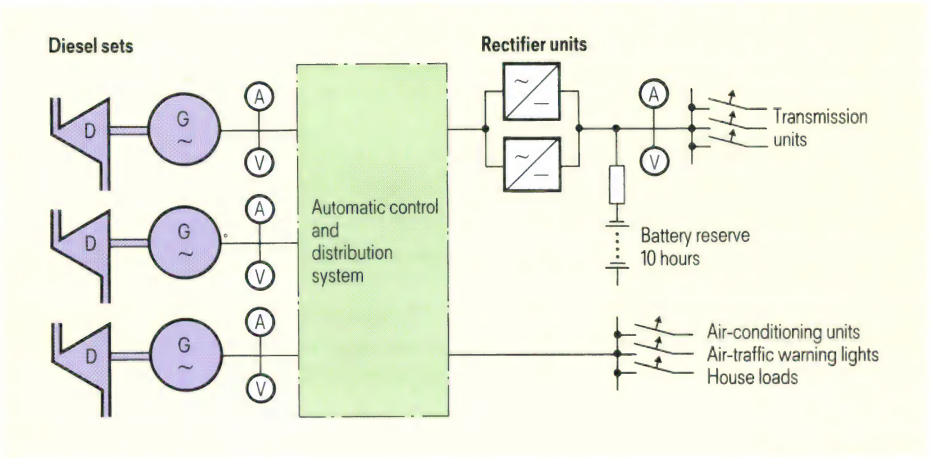
◁ Combined power system, comprising a solar generator and wind power plant, and producing 2 kW output power at 48 V



D Diesel set G Generator

Fig. 2 Functional circuit diagram of a triple diesel plant for powering a radio relay repeater station

System design

The crucial factors in choosing power facilities for self-contained radio relay stations are as follows:

- power requirement and accessibility of the station,
- supply reliability required for the station equipment,
- climatic conditions,
- standard of training of operating and maintenance personnel.

For stations with a high power requirement (>1 kW) it is usual to employ *diesel power plants* in the form of dual or triple sets (**Figs. 1** and **2**). In such an installation each set runs for 24 hours; at the end of this period the next set is started automatically to continue the supply to the loads for a further 24 hours. In the event of a failure the next operational set starts immediately.

In order to ensure that these power plants are able to maintain operation "round the clock", it is necessary for all the main functions of the sets to be monitored. Only then is it possible to initiate direct and specific action. This occurs, e.g. in the event of

- excessive engine temperature,
- deviation in generator frequency,
- loss of oil pressure,
- failure to start,
- generator undervoltage or overvoltage,
- overload.

Even the failure of an automatic cutout or engine circuit breaker causes the automatic diesel control circuit to switch over.

The sets, including the air and oil filters and the oil and fuel supplies, are designed to enable each set to operate for 1500 h without maintenance. Each diesel set has its own day tank which is automatically refilled from a common storage tank.

No-break power to the communication loads is maintained by adequately sized station batteries, which are floated or charged via rectifiers. It is normally necessary to provide additional reserve capacity for air-conditioning units and air-traffic warning lights.

In some countries the infrastructure is such that refuelling and maintaining such plants can be a difficult undertaking. Remote status signaling facilities are particularly important in such situations.

Owing to recent developments in radio relay systems leading to reduced power consumption, efforts now concentrate on the possibility of utilizing alternative energy sources. Depending on the geographic and climatic conditions it is now already possible for self-contained power supply systems with ratings of up to 500 W to operate exclusively from solar and (or) wind energy. The radio relay links on the Sinai peninsula and in the Sultanate of Oman, for instance, are equipped with *solar power plants* serving radio relay stations with a power requirement of 100 to 500 W [1, 2].

For loads greater than 500 W it is more economical to employ combined *solar and wind power plants* if sufficient wind is available. In the Sultanate of Oman three radio relay stations have been equipped with this type of combined system. Indeed, one of the stations has two wind power plants for a power requirement of about 1000 W. **Fig. 3** shows this combined power supply facility com-

Fig. 3 Combined power plant comprising solar generator and wind power system for 2 kW output power at 48 V

prising two wind power plants with an output power of 2×2 kW at a wind speed of 8 m/s and two solar generators with a maximum output power of about 3.5 kW. About 60% of the power is covered by wind power and 40% by solar energy. The wind power plants were planned on the basis of data from the Hamburg Maritime Weather Bureau indicating a mean wind speed of about 4 m/s. Planning data about the intensity of the mean insolation was derived from tables of solar radiation [3]. The forecast power budget for this station based on the sun and wind "supply" is shown in **Fig. 4**.

A storage battery ensures continued operation for a further ten days even on failure of both energy sources. Each energy source is connected to this battery via its own regulator to maintain or replenish the charge of this energy store (**Figs. 5** and **6**). An ampere-hour meter in the battery line registers both the ampere-hours taken out of the battery and the recharged ampere-hours taking into account the charging rate. In addition, this meter transmits a remote status signal as soon as the battery capacity falls below a given limit. This enables timely action to prevent deep discharging of the battery.

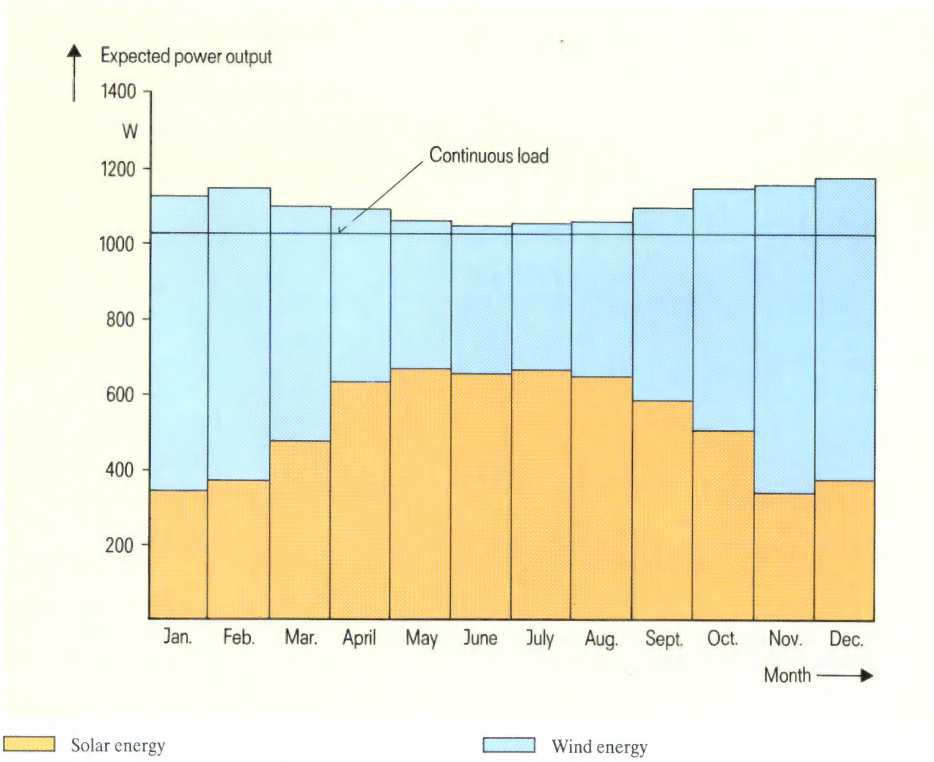
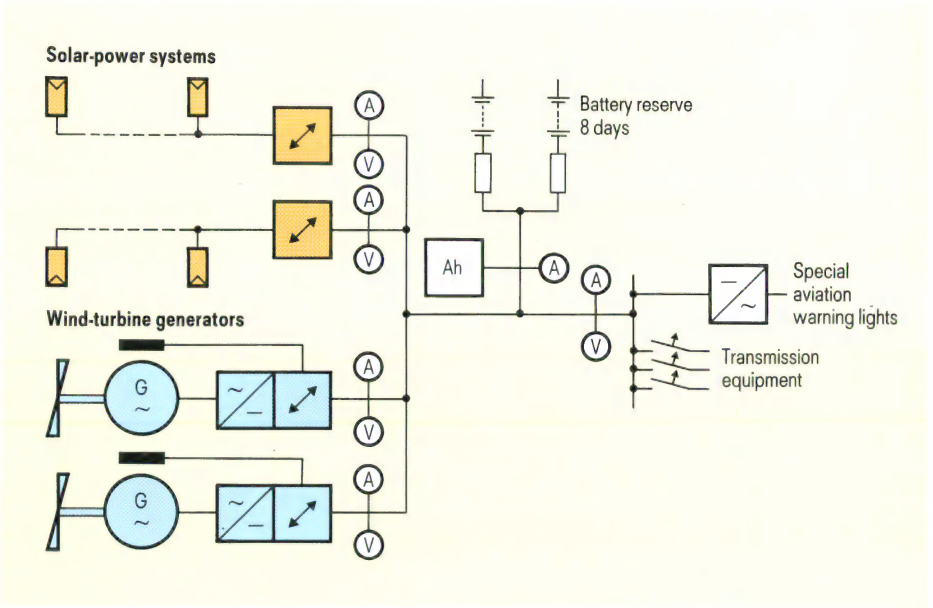


Fig. 4 Energy budget for a combined power plant, utilizing wind power and solar energy



G Generator

Fig. 5 Functional circuit diagram of a power plant operated exclusively with wind power and solar energy

Mechanical and structural features

All components are designed to meet the specific environmental conditions encountered at the site of installation. Crucial factors in this respect are corrosion protection, rot-proofing and low maintenance. Other features of the mechanical design are low weight (essential for transportation by helicopter) and simple installation with a high degree of preassembled components.

For relay stations located in remote and difficult terrain, shelters are employed. They are supplied complete with units for the transmission systems in accordance with the customer's specific requirements (**Fig. 7**). All that is required on site is to establish the connections. The dimensions of the shelters including the shipping and fastening facilities conform to ISO standards for containers.

For stations with a power requirement of up to 500 W and utilizing regenerative energy sources it is usually possible for the power supply equipment and radio relay system to be accommodated in one shelter.

A partition wall physically separates the batteries from the style 7R radio relay systems and the control and regulating equipment of the solar and/or wind power plants. The battery has a special rack which provides optimum space utilization.

When diesel units are employed to supply the power, e.g. for powers over 500 W, they are housed in a separate shelter. This ensures that engine vibration is not transmitted to the system units.

Shelter insulation and shade roofs prevent the system rooms from overheating due to environmental heat and insola-

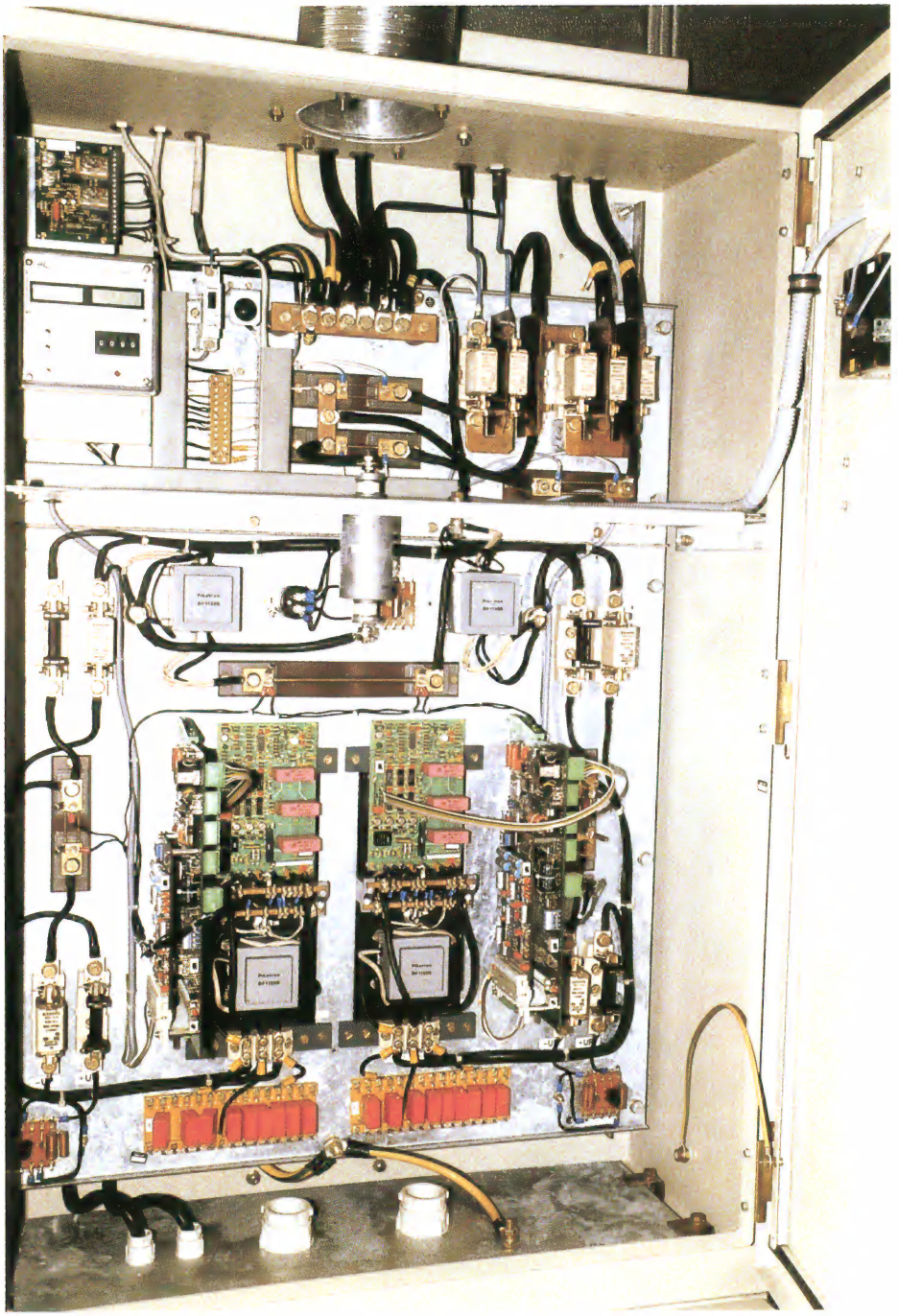


Fig. 6 A solar regulator designed for radio relay systems in Oman

tion. A passive cooling system [4] requiring no additional energy extracts the heat dissipated by the units inside the shelter (**Fig. 8**). Where power is derived from diesel sets, this function is provided by air-conditioning units.

The solar panels (**Fig. 9**) are of weather resistant, light-weight design. Their rugged, geometric structure meets both static and dynamic requirements based on wind speeds of up to 180 km/h. Uprights, erected on previously laid foundations and linked by crossrails, support the solar modules.

For shipping purposes the individual components are grouped into subpacks, allowing trouble-free transportation, even in difficult terrain. Copper busbars protected by box-section tubes provide simple wiring of the modules up to the junction box. They are then connected to the regulating equipment in the shelter via shielded underground power cables. The entire system requires no maintenance except for cleaning the modules at the specified intervals.

The wind power plants are also designed for low-maintenance operation (**Fig. 3**). At the top of the hot-galvanized steel tower (5.5 or 11 m high) is the freely rotatable system comprising the variable axis rotor assembly and the directly driven generator (**Fig. 10**). A tower mount sunk into the foundation enables the tower to be easily erected about a pivot using a hoist which is supplied. Three guys lashed below the top of the tower provide stability. The power and control cables connected to the sliprings in the rotating head assembly lead down inside the tower to a switch-box. Shielded underground cables provide the connection to the regulator in the shelter.

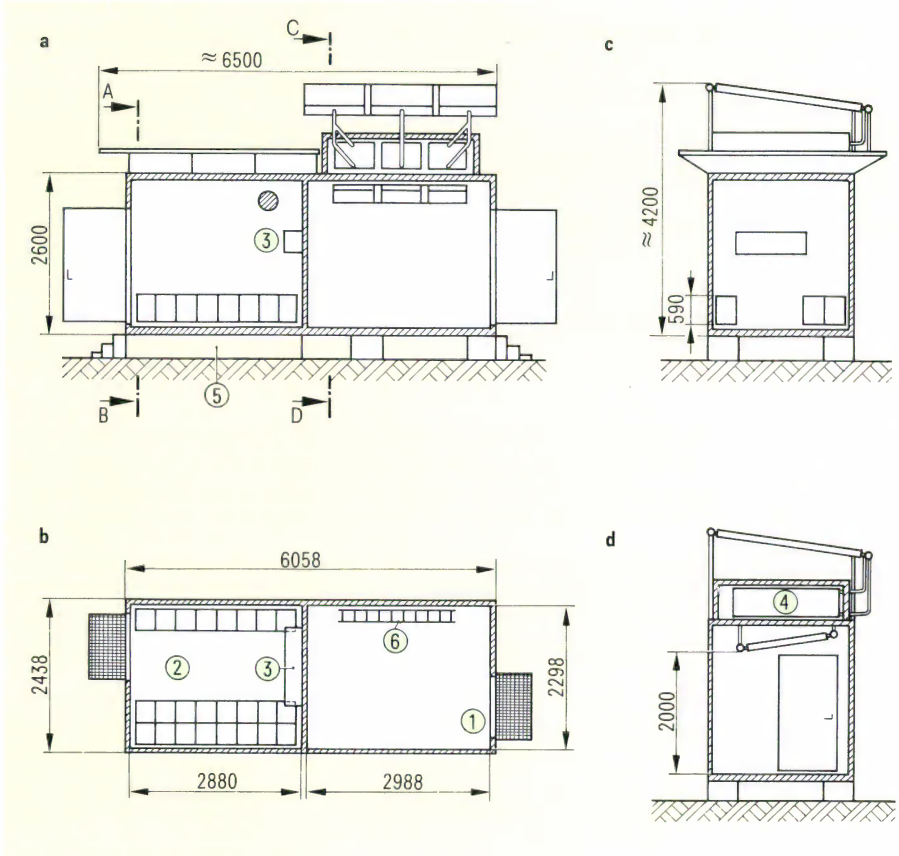
The system incorporates an automatic facility for overspeed control. Additional masses are geometrically arranged so that if the rotor exceeds its operating speed range, its blades are tilted about their longitudinal axis into an overspeed control mode. This prevents the rotor from operating at excessive speed under storm conditions. Once the speed falls within the operating range the rotor blades are gradually restored to their initial position via a spring as the torque subsides.

The overspeed control facility integrated in the generator can be operated via a switch in the regulator cabinet to shut the system down.

Self-stabilized wind tracking is governed by two factors: first, by the balance of masses between generator and rotor about the pivotal point (center of tower), and second, by locating the rotor blades in the lee of the tower, i.e. behind it (as viewed in the direction of the wind).

Cost comparison

When planning self-contained radio relay stations it is advisable to take the capital costs for the necessary power supply facilities into account at the outset. The planning aid shown in simplified form in **Fig. 11** can be used to obtain rough costings. It compares the relative cost of different types of power supply systems for a 400 W continuous load in each case.



① Room with communication equipment
② Battery room
③ Voltage regulator for solar cells
④ Passive cooling system
⑤ Foundation
⑥ Radio relay equipment

Fig. 7 Basic layout of a radio relay repeater station
a Elevation
b Plan view
c Section A–B
d Section C–D

Taking the conventional system, comprising a dual diesel set, rectifiers and battery (red), as the cost base at 100% (typical for power loads over 1 kW), the capital costs for lower-power plants with a regenerative energy source still appear to be relatively high. Thus, the acquisition cost of a dual wind power plant (blue) for a radio relay station requiring 400 W is 85% higher than that of the diesel plant. For a combined plant, utilizing wind power and solar energy at the same time (green), the cost is doubled. If the 400 W system is powered by solar energy alone the procurement cost is increased by a further 10% (black).

However, when post-commissioning costs are compared, considerably more must be spent on maintaining the diesel plants than on the solar and wind power plants. This is due to the fact that expenditure on such cost-intensive items as fuel supply, maintenance, engine specialists, vehicles etc. is reduced when wind power is employed because this system requires inspection only once a year. The situation is similar for solar power. This may entail a cost for cleaning the solar panels but this work can be done by unskilled personnel.

For stations with dual or triple diesel plants, the operating and maintenance costs incurred within two years can be considerable. For the Sinai and Oman

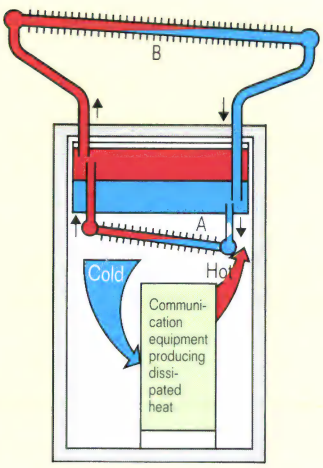


Fig. 8 Operating principle of a passive cooling system

Fig. 9 Radio relay repeater station with solar plant for 2.2 kW peak power and shelters with passive cooling system

Fig. 10 Wind power plant with hinge-over towers

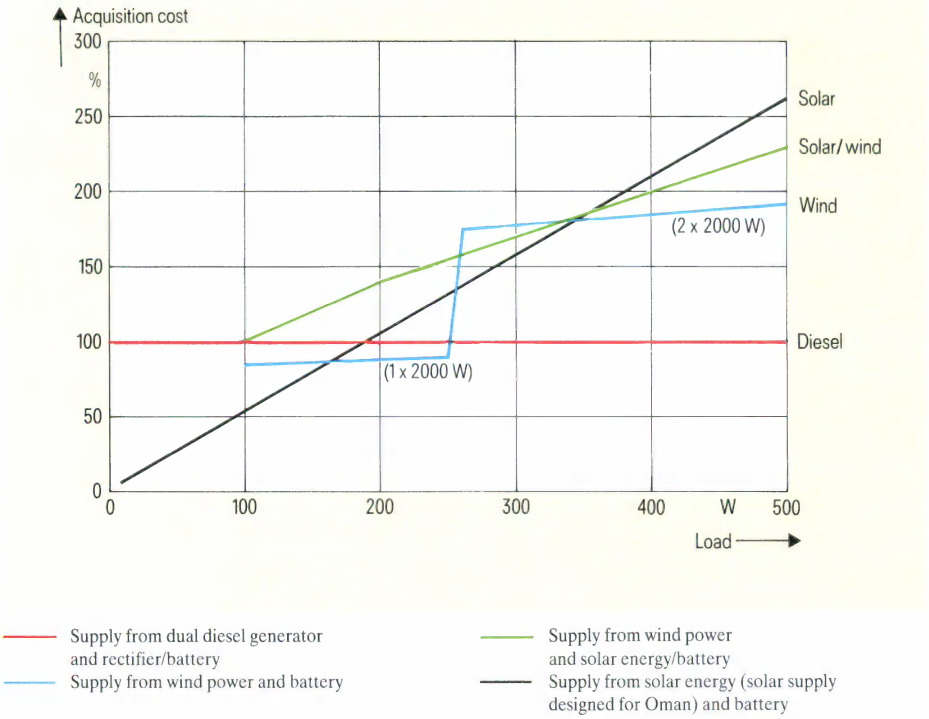


Fig. 11 Acquisition costs (excluding operating costs) for power plants with loads of up to 500 W, compared for four different systems (base 1985)

projects employing solar and wind power plants it is predicted that the initially higher acquisition cost will have been recovered after a mere seven years. There is also a greater probability that network operation in the projects employing regenerative energy will present fewer problems after handover to the clients than if diesel plants had been employed with their maintenance and fuel supply requirements.

In addition, it may be assumed that, as new developments occur in communication equipment and systems, there will be further power reductions. Thus, it is anticipated that regenerative energy sources will become increasingly applicable and cost-effective for powering self-contained stations.

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Siegfried Hofmann and Alfons Rendl

Designing Highly Reliable DC Power Supply Systems for Radio Relay Stations

For the no-break operation of radio relay stations, reliable and continuously available power supply equipment is essential. While the decentralized, system-associated power supply units for communication equipment can handle relatively large variations within their operating voltage ranges, the batteries require closely toleranced supply voltages if they are to maintain their full capacity and achieve maximum life. In order to prevent ac supply variations and other disturbing influences from affecting the dc side, regulated rectifier units are employed.

This paper describes the no-break dc power supply for communication systems as designed for two radio relay stations to cover different power ranges and meet the particular requirements of the Deutsche Bundespost.

Power supplies for the high power range

The Deutsche Bundespost employs centralized no-break dc power with an operating voltage of 60 V as the basis for the reliable operation of communication equipment. Standard radio relay towers are powered by plants rated from 1.5 to 100 kW. These plants are located in a separate equipment building at the foot of the tower. **Fig. 1** shows a dc power supply plant rated at 100 kW.

In some long-haul telecommunication towers designed for high power requirements (>20 kW) and large tower heights, the power supply plant is installed on one of the equipment floors at the top of the tower. **Fig. 2** shows the basic configuration of a no-break dc power supply for a standard radio relay tower.

If local conditions allow, the power supply plant is fed from the commercial power network for reasons of economy. The commercial power network, however, cannot always meet the strict requirements for supply availability. Even in highly reticulated ac supply net-

Fig. 1 DC power supply plant rated at 100 kW for the telecommunication tower in Frankfurt (Main)

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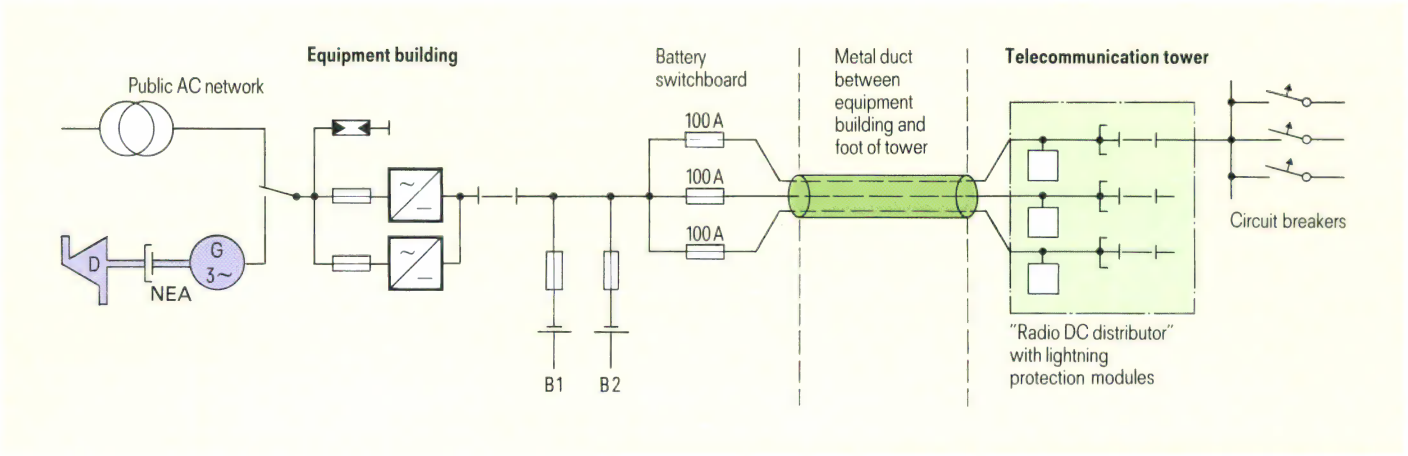

B Battery connection D Diesel set G Generator NEA Standby ac power plant

Fig. 2 Block diagram of a no-break dc power supply (float operation) in the equipment building of a radio relay tower

works, short-duration interruptions of up to a few hundred milliseconds occur relatively frequently. Indeed, long-duration disturbances ranging from a few seconds to several hours cannot be eliminated. An automatic standby ac power plant is therefore provided as passive redundancy to maintain the supply in the event of public ac failures >2 s. The commercial power itself, however, is not suitable for feeding communication systems directly. In order to power the loads on a completely no-break basis, therefore, a dc power supply is provided and float-charged via lead-acid batteries.

DC power supply

The dc power supply plant referred to above is assembled from several parallel thyristor-controlled rectifiers to suit the power requirement. These rectifiers are available in a range of sizes from 25 to 1000 A.

The power supply plant incorporates redundancy in order to ensure reliable station operation even in the event of an equipment malfunction. The excess power thus available is utilized to charge the batteries when the ac supply is restored.

Battery switchboard

A battery switchboard is provided as the central connection unit. It is used for paralleling the rectifiers and for connecting the two batteries to the bus or charging bar. The load fuses are also located here. In addition, it incorporates the central rectifier control and monitoring facilities, an overvoltage limiting unit

Fig. 3 A typical low-power radio relay station

and an indicating facility for detecting all the fault signals occurring in the plant.

"Radio dc distributor"

The individual equipment floors are supplied from the battery switchboard via cables. These cables are dimensioned to provide a maximum permissible voltage drop of 1.6 V. The supply cables are terminated in the "radio dc distributor". From there the rack rows accommodating the communication loads are fed via individual lines. These dc distributors can be provided in any quantity depending on the size and number of equipment floors.

Power supplies for the low-power range

Remote radio relay stations (**Fig. 3**) are supplied using dc power plants rated up to about 1.5 kW. The basic configuration of such plants is shown in **Fig. 4**.

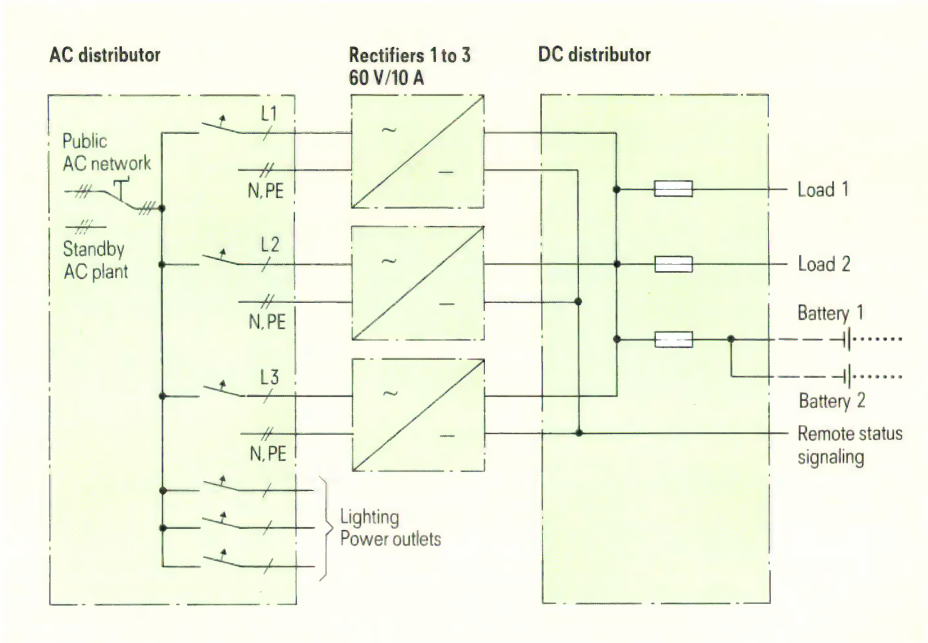

Fig. 4 Block diagram of a secure low-power dc supply

During normal operation the stations are fed from the commercial power network. Prolonged commercial power failures, due for instance to power line damage, can be covered by the use of mobile standby ac power plants. The six to eight hour battery reserve of the power supply plant allows the standby plant to be located centrally for deployment as required.

An ac distribution system incorporates the circuit breakers for connecting the rectifiers and the ac loads. The dc distribution system following the rectifiers incorporates the fuses required for the communication loads and the station battery.

Fig. 5 shows a typical station configuration. A rack frame enables the rectifier units as well as the ac and dc distribution systems to be integrated directly into the style 7R rack rows. The units can also be secured directly to the wall. All internal connections between the units consist of connectorized cables. This 10 A rectifier system, with its space-saving installation, easy replacement and ready expandability, is particularly suitable for use in radio cabins and equipment shelters.

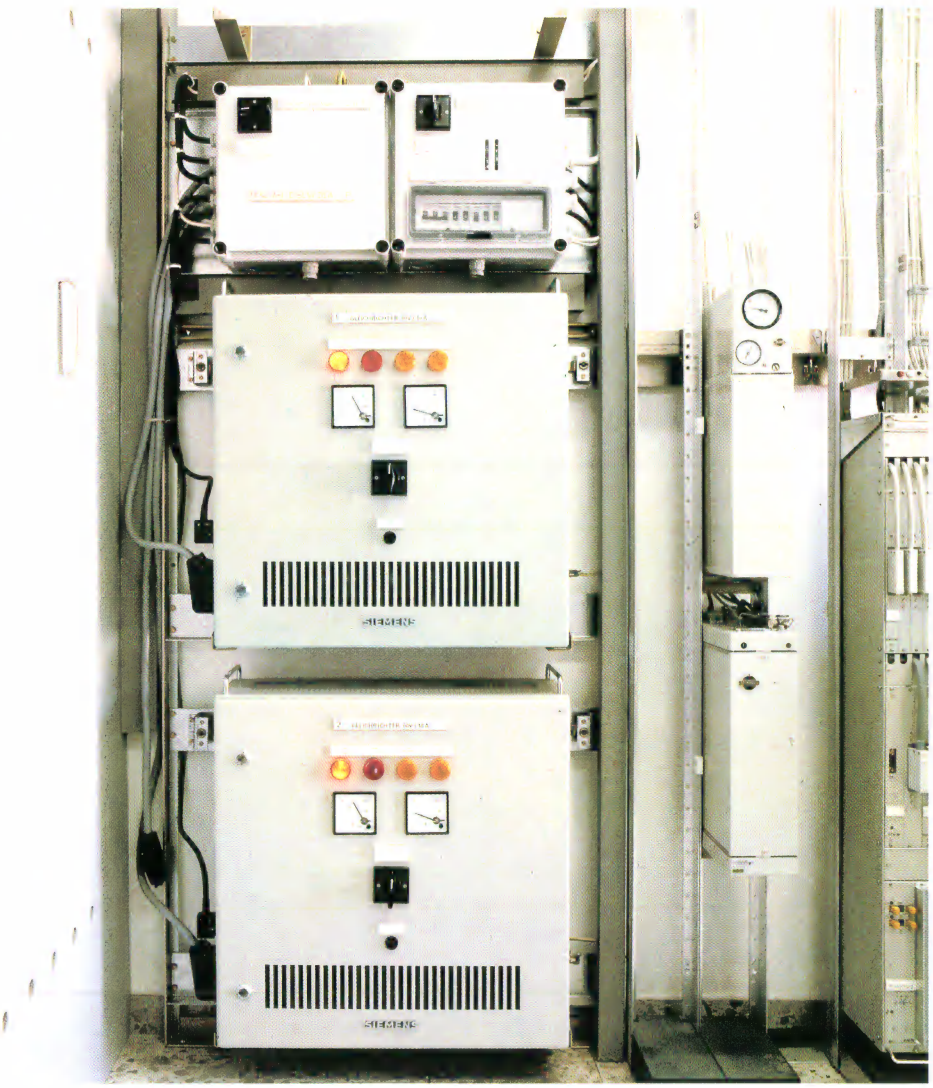

Fig. 5 Secure dc power supply for a low-power radio relay station

DC power supply

The dc section of the plant usually consists of three thyristor-controlled rectifiers operating at 67 V and 10 A. These

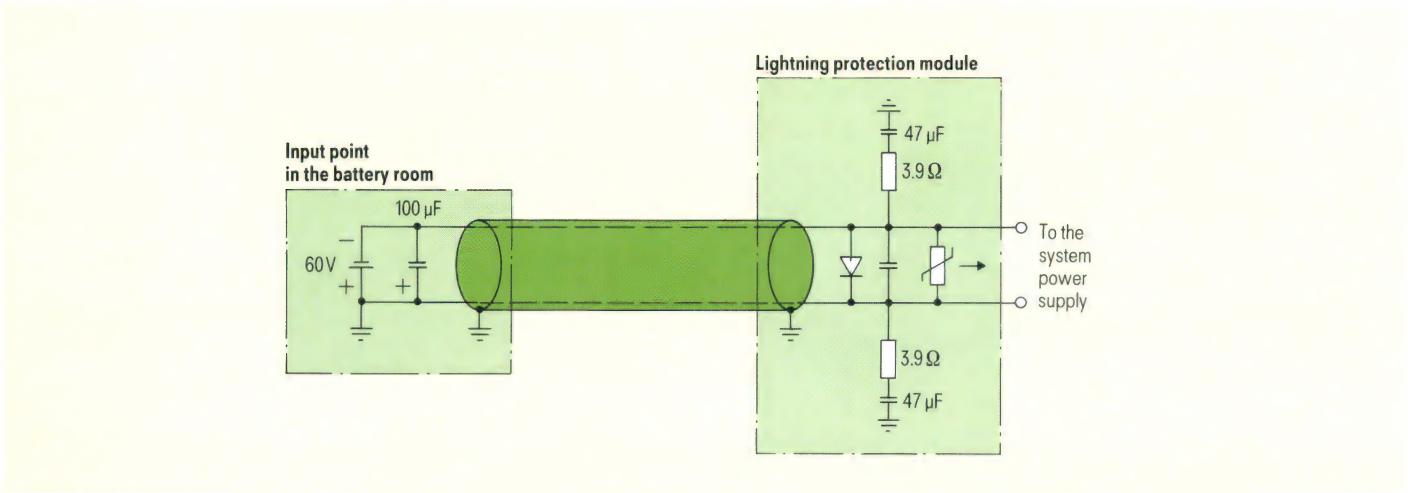

Fig. 6 Lightning protection arrangements on the dc supply cable

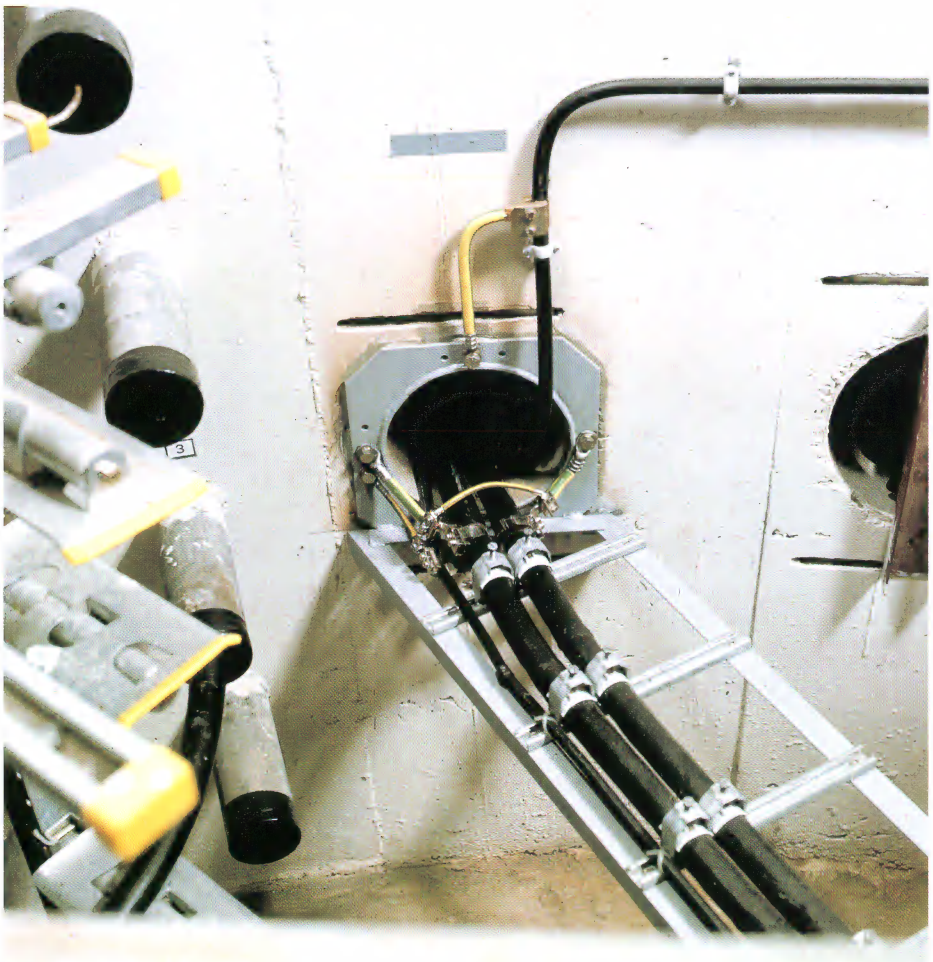

Fig. 7 Outlet of the lightning protection duct at the foot of the radio relay tower

rectifiers are suitable not only for directly supplying radio and line equipment but also for charging and float-charging the 30 cell lead-acid battery. They require no forced ventilation, while their convenient layout and plug input and output connections ensure maximum ease of maintenance.

The rectifiers are regulated in accordance with the taper charge method, and the changeover from trickle-charging (67 V) to charging (70 V) of the batteries is effected automatically. An electronic voltage monitor is provided for the protection of transmission equipment forming the load.

The rectifier units are generally configured for $(n+1)$ operation, so that, even if one of the units fails, the supply to the loads is not impaired. It is possible to apply a forming charge to the battery during operation; for this purpose one of the batteries is disconnected and the redundant unit is switched to special charging at 2.7 V per cell.

Distribution equipment

An ac distribution system is used for connecting the rectifiers on the ac side as well as for connecting and protecting ac loads. It also permits changeover from the commercial power supply to the standby ac supply. The status signals from the plant are detected centrally in the dc distribution system and are fed via a master signal switch to the distributor, a distinction being made between "urgent" and "non-urgent" alarms.

Lightning protection

Owing to their exposed locations, radio relay stations are subjected to "atmospheric discharges". Since these discharges would give rise to overvoltages in the long supply lines, shielded cables are always used for connecting the power supply plant to the individual loads. In order to ensure that the systems are not put at risk, it is absolutely necessary for all parts of the plant to always be at the same potential with respect to ground (**Fig. 6**). For this reason all cable connections between the equipment building and the foot of the tower are run in a metal duct (**Fig. 7**) which is bonded at as many points as

possible to the reinforcement of the tower and equipment building. The shield of the feeder cable is connected to the metal structure of the power supply plant, to the start and end of the metal duct and to the planar cable runway in the equipment building via the shortest path. The resultant "Faraday cage" has the effect of considerably reducing the grounding resistance of the protective grounding system. Any overvoltages exceeding the permissible level are finally limited by the lightning protection modules (**Fig. 8**) located on the equipment floor.

All these measures provide optimum protection for the dc power supply. In addition, lightning protection arrangements are provided in the ac distribution system for protection against overvoltages from the commercial power network.

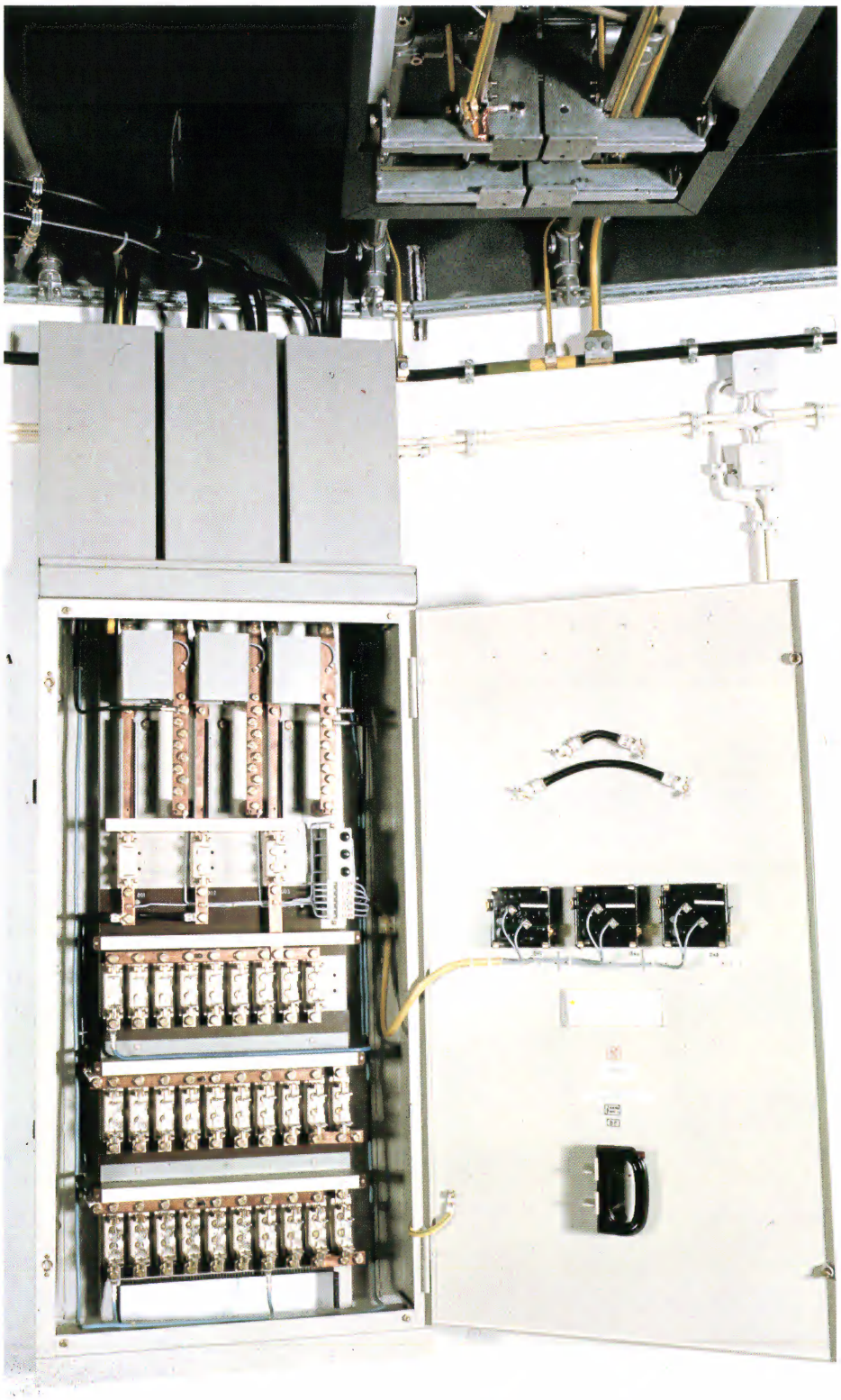

Fig. 8 Lightning protection modules mounted in the 16-kW "radio dc distributor"

Summary

Thyristor-controlled dc power supply technology, which has proven itself for over 15 years, will continue, through its matured variants, to provide radio relay stations with an optimum source of energy adapted to the requirements of communication equipment. Through precautionary protective measures and sizing guidelines, as established in cooperation with the Deutsche Bundespost, a 100% availability of the power supply is achieved.

Bernhard Boch and Siegfried Hofmann

No-Break AC Power Supply for Earth Stations

With the present-day density and variety of communication networks it is necessary for their transmission paths to be available at all times. In order to ensure this, the power supply systems must maintain continuous operation. Extensive provisions to ensure that the supply is maintained at all times are particularly necessary at earth stations, with their high requirement for no-break ac power. This paper describes the configuration of a state-of-the-art power supply system for an Intelsat Standard A earth station.

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Munich

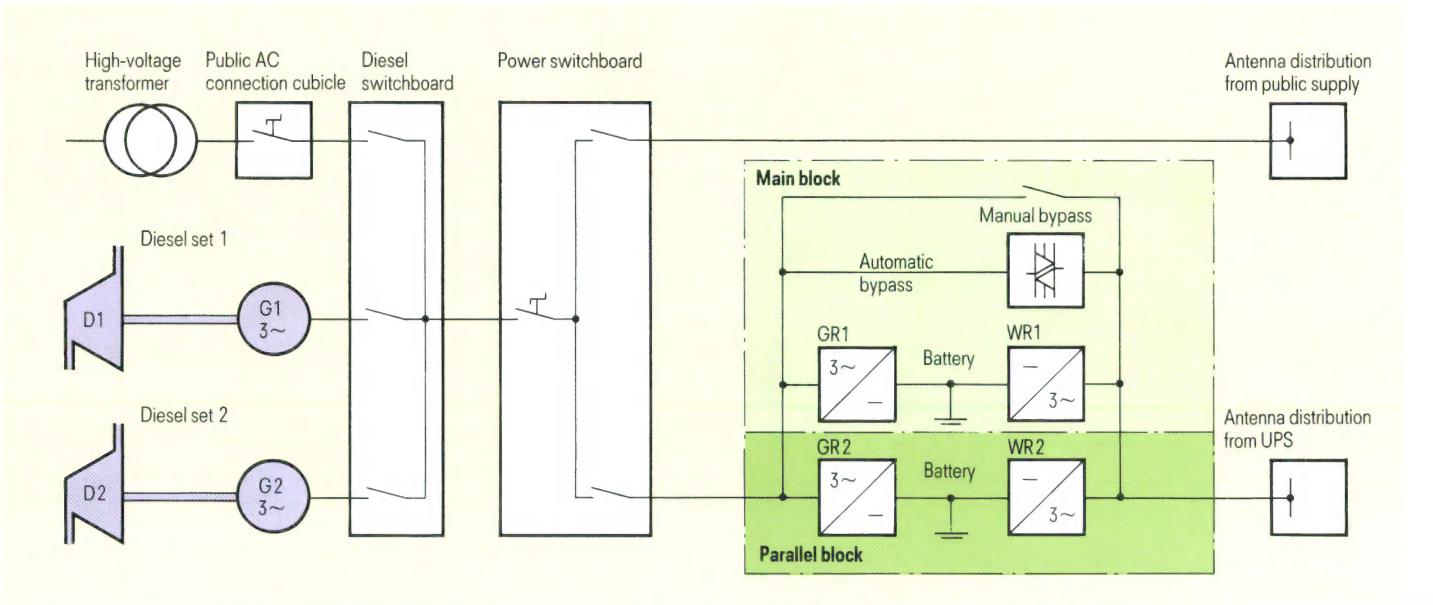
System design

In May 1985 the Intelsat earth station, Lempira II, was commissioned in Honduras. In order to provide a firm source of energy, a redundant, no-break ac power supply was installed. The basic configuration of the power supply is shown in **Fig. 1**.

During normal operation, the local high-voltage network (32 kV) is used via a transformer to supply the ac loads and the uninterruptible power supply system. Cover for prolonged commercial power failures is provided by two standby ac power plants, each producing 300 kVA. Loads, such as lighting and air-conditioning, antenna servomotors etc. are connected directly to the commercial power network or to the standby ac power plants because brief failure of these supplies does not directly impair station operation. All transmission loads, such as the transmit, receive and monitoring equipment, are supplied via *uninterruptible inverter plant*. This comprises two parallel power supply blocks, each supplying half the load and containing a thyristor-controlled rectifier, a 180 cell lead-acid battery and a three-phase inverter. Passive redundancy is additionally provided in the form of an automatic static bypass switch so that in an emergency the loads can also be supplied directly from the commercial power network or from the standby ac power plant.

Operation

For the system described, a *300 kVA high-voltage transformer* was installed to step the 32 kV high-voltage supply down to the local low-voltage supply of 120/



D Diesel set G Generator GR Rectifier WR Inverter

Fig. 1 Functional circuit diagram of the power supply system for an earth station

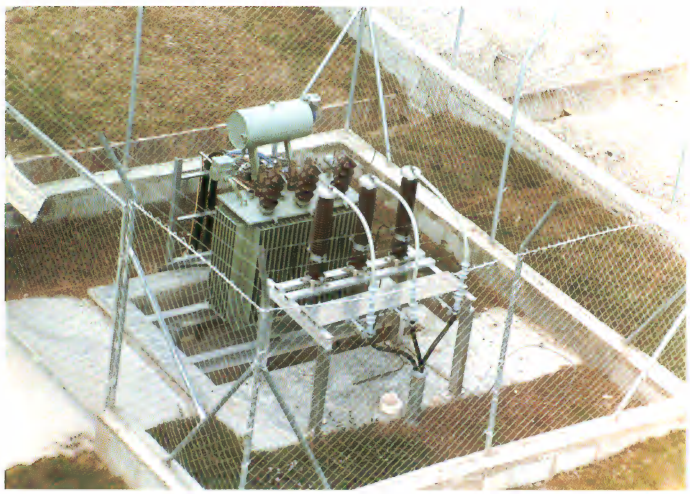


Fig. 2 The 300 kVA high-voltage transformer furnishes the local low-voltage supply of 120/208 at 60 Hz

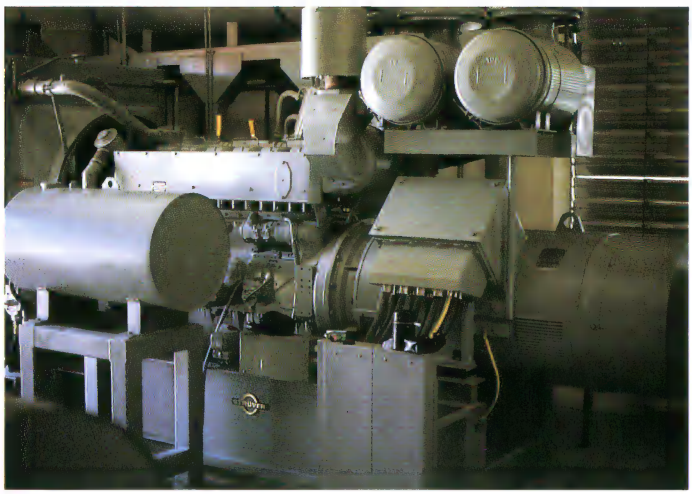


Fig. 3 Two such fully automatic 300 kVA standby ac power plants cover any commercial power failures

208 V at 60 Hz (**Fig. 2**). The connection was established via underground cables. Protection against overvoltages due to atmospheric discharges is provided on the input and output sides by surge arresters. Commercial power failures are covered by the two fully automatic *300 kVA standby ac power plants* (**Fig. 3**). During prolonged disturbances these plants operate alternately on a 12-hour cycle. A central control cabinet, containing the modular equipment for monitoring the commercial power supply, the generator and the diesel engine, also houses the connections for the individual loads. From here it is possible to check all the important operating parameters, as well as current, voltage and load power at any time on the easy-to-read meters.

The fuel supply to the diesel plants is also automated. The diesel tank located in the station building is refilled from a $2 \times 10{,}000$ l storage tank by an electric fuel pump which responds to signals from a float-operated controller. Main-

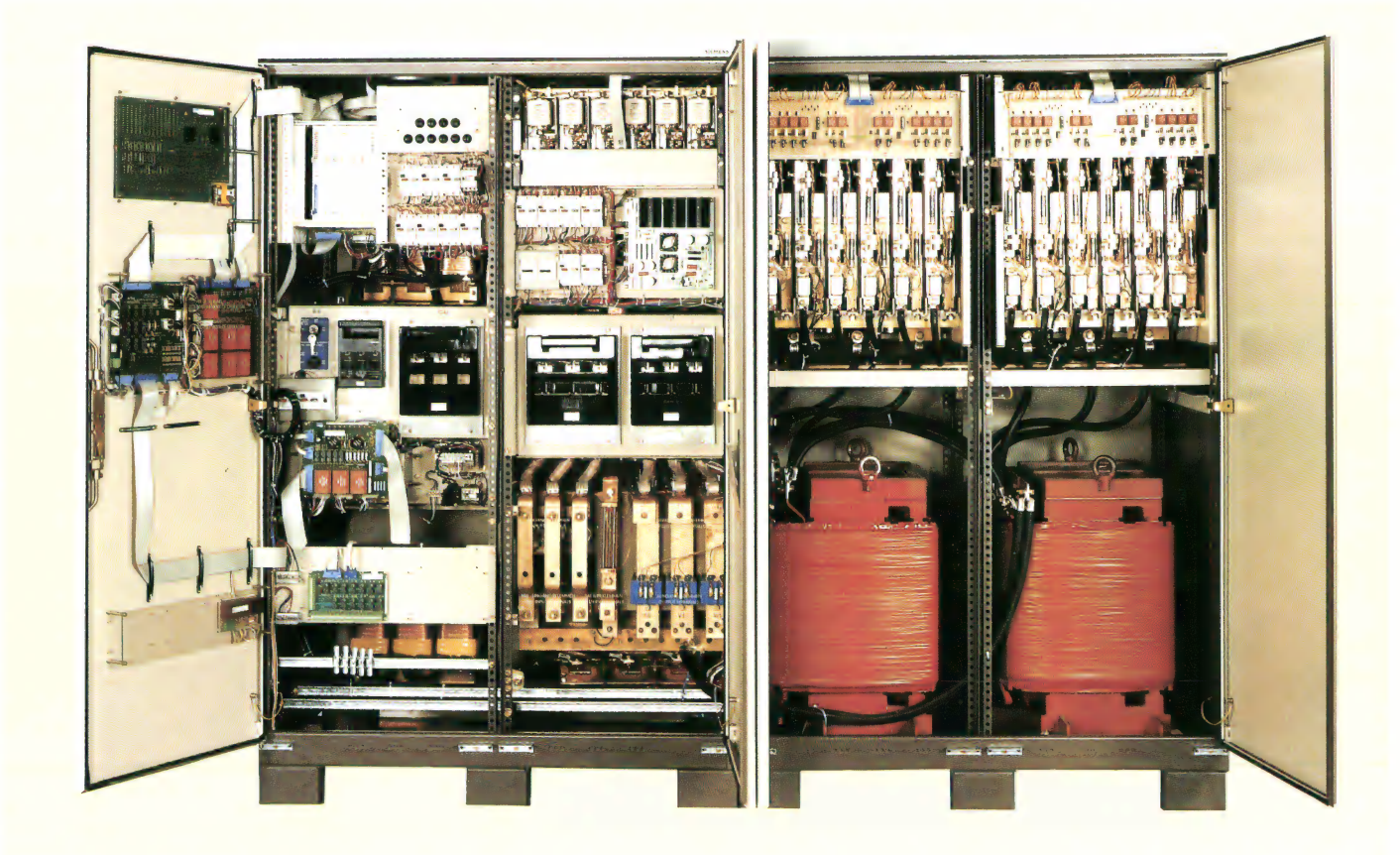


Fig. 4 Main block of the uninterruptible power supply (UPS) system

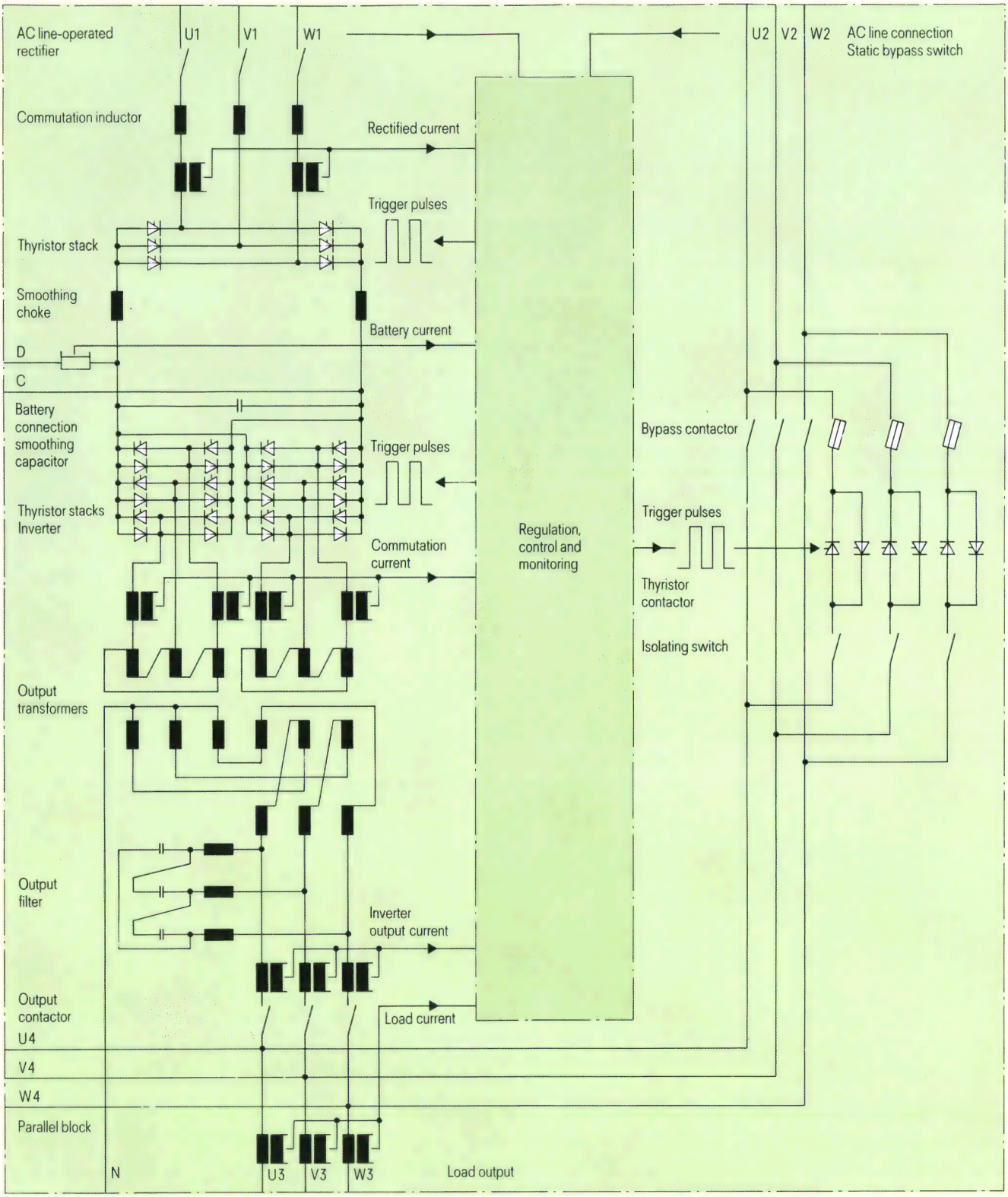


Fig. 5 Functional circuit diagram of the uninterruptible power supply (UPS) system

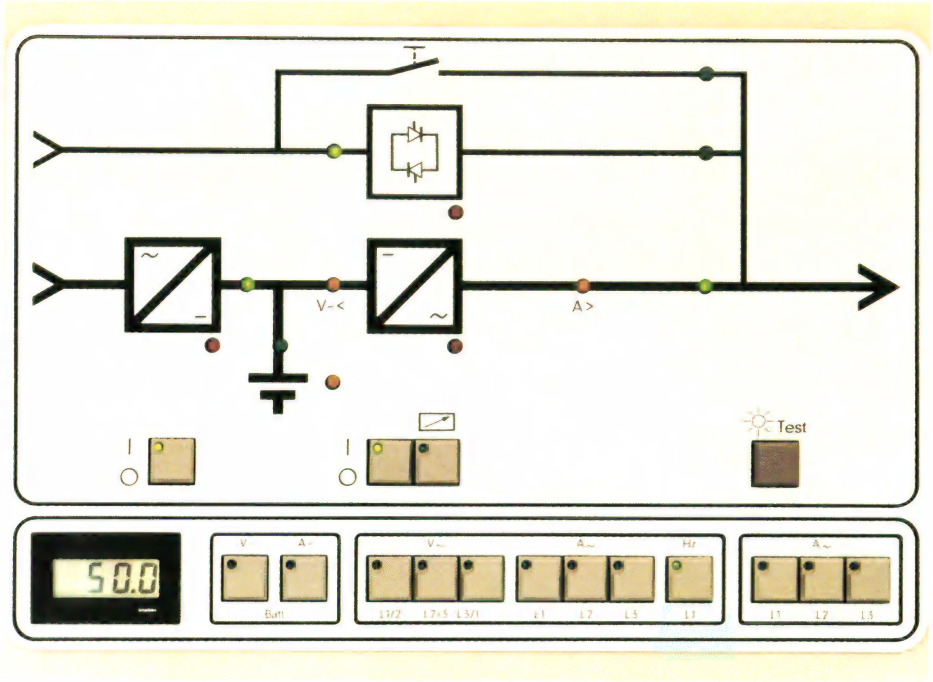


Fig. 6 Control panel of the inverter plant, the display indicates operating and fault signals

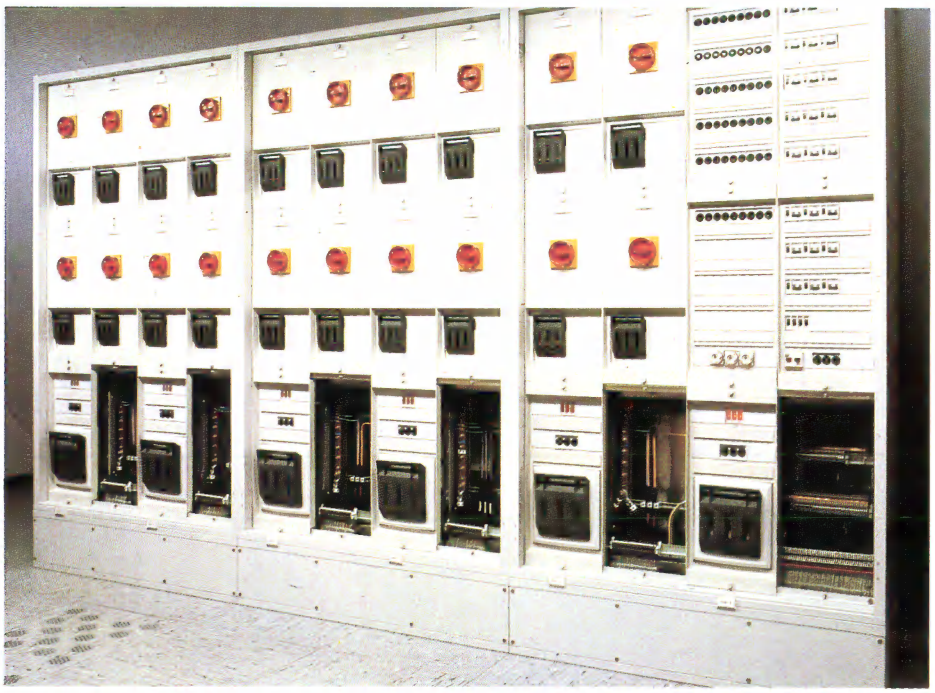


Fig. 7 AC distribution system in the equipment room of the antenna system (commercial power supply and uninterruptible power supply)

tenance of the starter batteries also requires particular attention because it is upon this that the reliability of the standby ac power plants in large measure depends. In order to compensate for self-discharge losses during the periods of inactivity a power line operated trickle charger is provided.

Central distribution of the power is performed by a *power switchboard*. This is used to connect the loads which are supplied directly from the commercial power network or from the standby ac power plants. A second output is used for connecting the uninterruptible inverter plant.

For protection against commercial power interruptions, voltage or frequency deviations and breaks on switching between public and standby ac supplies, the transmit and receive systems are coupled to an uninterruptible power supply system (UPS system). The system employed here consists of two redundant UPS blocks (**Fig. 4**); the functional circuit diagram is shown in **Fig. 5**.

A thyristor-controlled rectifier converts the input ac voltage to 360 V direct current. This intermediate dc circuit is supported by a 180 cell lead-acid battery connected in parallel. This battery, float-charged by the rectifier, ensures that there are always four hours of energy available in the intermediate dc circuit. On restoral of the commercial power the rectifier reverts automatically to charging each cell at 2.33 V in order to recharge the battery. A following inverter converts the intermediate circuit voltage to the regulated three-phase load voltage. If this voltage deviates from the nominal by more than 10%, a static bypass switch transfers the load to the public network without interruption. Both operating and fault signals are indicated on a display in the control panel of the inverter plant (**Fig. 6**) and are forwarded from there to a central location.

Installed in the equipment room of the antenna system is an *ac distribution system* for connecting the loads to the no-break ac power supply (**Fig. 7**). The fuses of the various load circuits are also located at this central point to permit simple and convenient operation and inspection.

Summary

More than twenty years' experience in the application of static inverter plants for feeding communication systems confirms that they provide a very high supply reliability. A power supply system, comprising everything from the high-voltage transformer to the antenna distribution system and designed in conjunction with the Production Planning Department, will continue to be the basis for reliable earth station operation in the future.

Rudolf Gold and Helmut Schwinghammer

Project Planning and Surveying of Communication Networks

Project engineering for communication networks is assuming increasing importance because of the growing attention that must be paid to local and national conditions in addition to reliability and economy. Siemens, through its presence worldwide and experience gained from completed projects, is familiar with many of these problems. This combined with many years of technical experience in the transmission sector enables Siemens to plan projects which are tailored to the client's requirements and provide future-oriented, cost-effective solutions in recognition of the investment they represent.

The following article summarizes possible project planning approaches with reference to actual examples and selected areas of main interest.

Network structure, identifying the services required

The requirements that project planning must address in practice are extremely varied and can be met only by cooperating closely with the client's agencies. The products and services provided differ widely according to the client's requirements and range from construction documents through complete network planning including infrastructure in the case of turnkey projects.

The first step in planning any network project is to specify the transmission units. A distinction is drawn here between two main packages:

- telephone and data transmission networks, and
- television and sound broadcasting networks.

The capacity of a telephone transmission network is essentially determined by the demand figures for the switching equipment. Although determining traffic flow and traffic relations is not the subject of the present article, this is available from Siemens in another project planning package.

The traffic groups required on the transmission side of the switched network are obtained from trunking plans or traffic capacity tables which provide information on the size of transmission circuit groups, interface conditions, traffic relations and expansion.

In the switched network a distinction is generally drawn between the subscriber, local and long-distance networks. The transmission links may support circuit groups from all three networks depending on economic considerations. However, separate routing is usually preferred for operational reasons. Smaller circuit groups nevertheless have to be provided for special services, service channel links and dedicated circuits, the requirement for which can only be identified in close cooperation with the local agencies. As a rule of thumb, they are on the order of 10 to 20% of the circuit groups required for dial-up connections.

Data and telex networks are combined in separate superimposed network groups or integrated in the telephone transmission network. The routing in this case broadly follows the switching arrangements.

Subscriber networks within towns and communities are based largely on copper cables. Remote subscribers along the routes of transmission systems and certain subscriber nodes are creating an increasing need for transmission equipment. New applications for transmission equipment are also emerging in the subscriber network with the introduction of new services, such as broadband communication and ISDN.

Local networks employing analog systems consist largely of audio cable links. With the introduction of digital technology, these links are being established wherever possible via digital transmission systems with a suitable digital interface (e.g. 2 Mbit/s) and, increasingly, with optical waveguide systems. The selection of transmission systems in the local network is largely determined by the availability of manholes and existing cable routes.

A local network needs to be highly interconnected in order to be reliable. The alternate routing thus provided can be economically established by radio relay systems. Since the growth rates particularly in these networks can vary very widely, the expansion capacities of these systems should include adequate provision for future requirements. In order to provide the necessary flexibility, it is advisable to install central distributors (e.g. 2 Mbit/s).

With the phased introduction of digital switching systems, the arrangements for

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◁ The economical construction of radio relay stations, even under extreme environmental conditions, is made possible by proper station planning and low-maintenance power supply systems with passively cooled shelters. Pictured here is a radio relay station in Oman

linking with existing analog exchanges is a specialized area of project planning. This usually entails on-site investigations in order to quantify the interfaces required with the associated analog-digital converters and signaling converters. The local network of Muscat in the Sultanate of Oman is an example of such a digital network [1], incorporating analog exchanges and alternate routing between stations (**Fig. 1**).

Long-distance networks still account for the majority of the project planning effort on transmission systems because of the great distances to be spanned. The transmission systems are selected according to geographic conditions, local security considerations, maintenance and economic aspects. On radio relay routes in particular, station site and path selection are among the main project planning tasks which can only be resolved in conjunction with a survey.

A high level of intermeshing provides the long-distance network, like the local network, with a higher link availability and should be given special consideration when planning the network. Network nodes with alternate route switching can further enhance reliability.

Television and sound transmission networks require a different structure from that required for telephone and data transmission. With regional regulations, political boundaries, agreements between PTTs and ministries, it is important for project planners to consider national requirements as well as economic and operational factors. The transmitter network (program circuits), regional studio networks and national program buses are different in this respect [2, 3].

Transmitter networks are usually unidirectional feeder links between the studios or switching centers and the transmitters dispersed about the country. The links are established primarily via radio relay systems and usually with the same routing as the telephone system routing.

Regional studio networks are provided for transmitting television and sound programs between the originating centers and the nearest switching center. Since the link is usually located in an urban area, it is necessary to take local building into account when specifying the transmission medium. For centers originating a high volume of programs it is advisable to provide dedicated feeders.

National program buses are required for links between the regional studios, the switching centers of a national network and for national and international program circuits.

Switching centers are therefore employed to optimize the use of channel time available for sound and, in particular, for TV programs. Computer-controlled and manually operated distribution matrices are available for this purpose. Siting the distribution matrices within a national program network is an aspect of project planning which is heavily dependent on the local conditions referred to at the outset.

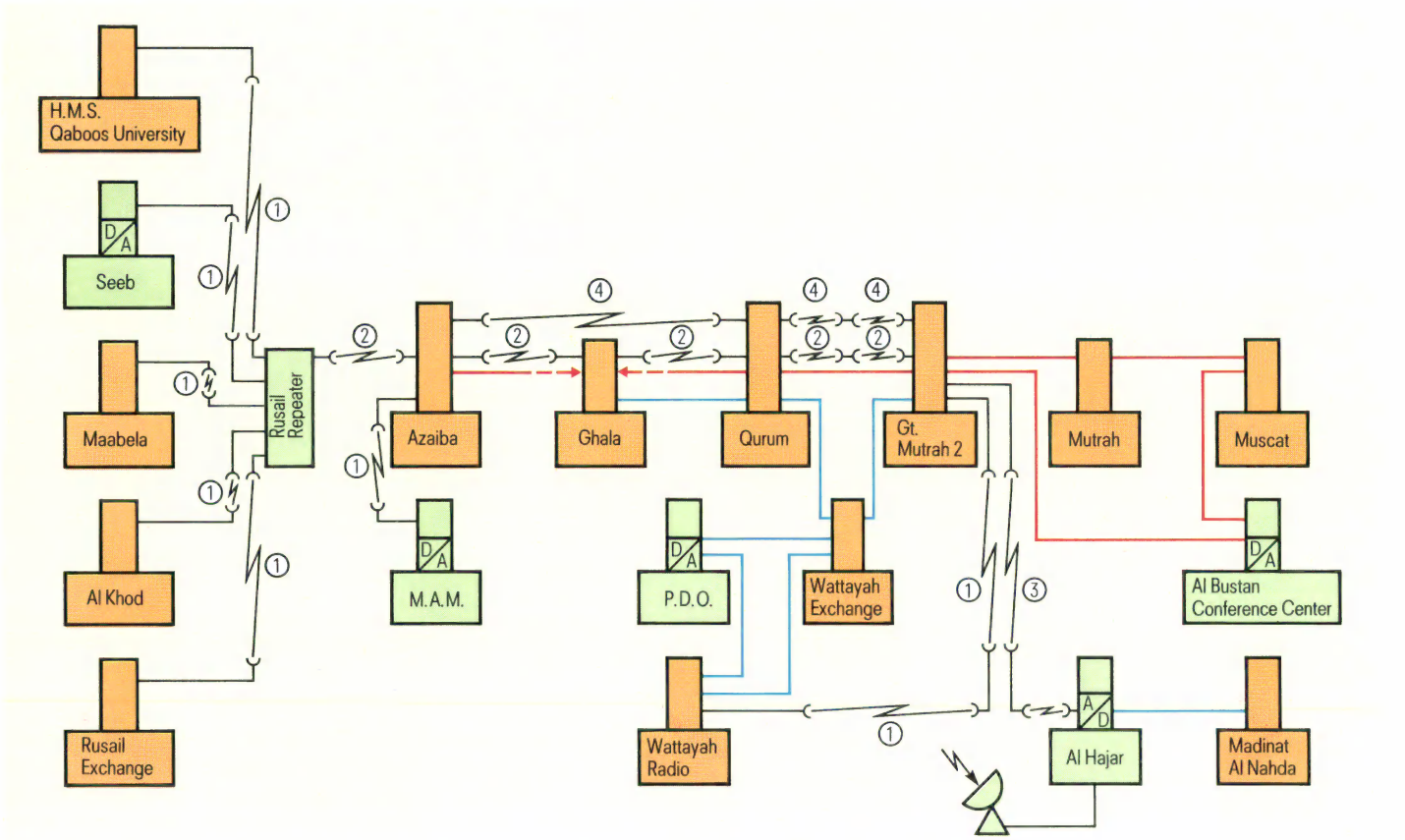

Fig. 1 Structure of a local network employing various long-range transmission systems as exemplified by the Muscat local network

Preparatory operations for the survey

Once the demand for the network structure has been established, the preparatory work for a survey and the actual selection of the paths can begin. The siting of the individual switching and data centers, studios and TV/sound transmitters has a considerable impact on path selection. Site selection and preliminary path selection preparatory to a survey must be based on good, up-to-date maps. In spite of all the technical aids, a "good," i.e. up-to-date, map is still the most important item.

The success, failure and cost of the project depend in no small way on the availability of maps which are available from survey offices or cartographic institutes, but are subject to security restrictions in many countries. In such instances, acquiring this material can be one of the most difficult aspects of the survey phase.

Of particular importance in preparing for the radio relay survey are maps on the scale 1:50,000 with contour lines and vegetation data. In the course of numerous projects Siemens has acquired a considerable library of maps which is constantly being expanded and renewed. These maps allow various alternative path routings to be selected "on the drawing board," thus considerably reducing the work of the subsequent survey.

The planning of cable routes also requires good maps in order to reduce the work involved in the survey. Maps on the scale 1:10,000 are, however, restricted to the more immediate vicinity of roads and should be used in conjunction with ducting diagrams and the routing diagrams for other services (gas, water, electricity supply).

Survey, survey methods and survey equipment

The investigation of local details is carried out as part of a survey program. Some of the results of these survey investigations are evaluated on site, others are fed into the detailed technical planning process. These activities are supported by the use of special computer programs. Inquiries into local opinion, environmental control, religious and cultural sites etc. are required in order to avoid obstacles in the area during path selection and subsequent construction work. In Africa, for instance, failure to detect a religious site not apparent to Europeans can delay construction by several months. In other countries it is important to check the extent to which tower and access roads can be built without conflicting with the local authorities.

The survey team is dispatched with a work schedule varying in size according to the type of survey. This team is usually joined by personnel with local knowledge drawn from the ranks of the client organization and by other personnel from Siemens' international network of branch offices (**Fig. 2**).

The following types of survey are undertaken individually or in combination depending on the task and the network configuration.

Station survey

The purpose of this survey is to acquire station-related data so that the plans for a facility or station can be adapted to suit the current, verified situation. The results can be of far-reaching importance, for instance, when an existing power supply system turns out to be inadequate, when an earmarked tower is already overloaded or when a new, multistory building is being erected in the line-of-sight of a radio relay station. Moreover, existing buildings must be examined for any conversion work that may be required.

Site survey

The site survey is intended to verify sites selected from the maps and to obtain the broader information required for project planning. There is no lack of evidence from examples around the world to show that basically any location is a suitable site for a station (except that some are better than others). Nevertheless, the client expects the best of those available. The site selected is a compromise between many different factors, ranging from access, tower height, availablity of power through to such non-quantifiable criteria as architectural or environmental aspects.

Path survey

Each path has critical sections and problem zones. The purpose of the path survey is to verify path details obtained from the maps and, in addition, to identify reflection points as well as weather and climate-related factors. A primary task of the path survey is to collect data on the soil structure, and on the frequent formation of fog or bodies of water which may lead to fading. Experience gained in the critical area of propagation in such locations can be crucial to the subsequent reliability of the link. On cable routes, particular care is required in identifying special hazards, such as wadis (dry riverbeds) in desert areas (**Fig. 3**).

Evaluation of the path survey may result in the original routings being modified or – in extreme cases – a switch to other transmission media. It is particularly important in such cases to advise the clients of the problems and propose alternatives in order to obviate subsequent damage.

Propagation survey

In undeveloped, unmapped areas and in zones of problematic microwave propagation, planning as such is possible only to a limited extent. In such cases an electrical test on site is the only way of clarifying whether a radio link between two wanted locations is possible and whether it will provide the specified results. The expense of such operations is understandably high. A propagation survey for radio relay links is, therefore, only considered when all other ways and means have failed. For mobile radio systems where area coverage is required, it is advisable to always carry out a propagation survey.

Photogrammetric survey

A photogrammetric survey can replace or supplement the propagation survey in providing the geographic data required for planning a radio relay link. This involves taking a series of aerial photographs of a defined area along the planned route to form a map detail. Here again, preparatory work is required at both terminal locations. The disadvantage is that lengthy analysis is required to determine success or failure and this result is usually not available on site. Such work is carried out by specialized firms.

Fig. 2 Actual surveying activity in difficult terrain

Fig. 3 Problematic site and soil formations on a cable route. Dry riverbeds (wadis) are problematic soil formations on cable routes

Subsoil survey

If soil conditions are unfavorable (swampy, sandy, rocky/gravelly) the path survey may have to be supplemented by a subsoil survey to obtain reliable soil data for optimizing the design of tower and building foundations as well as the construction of access roads and other facilities. In extreme cases, subsoil surveys are necessary in order to obtain reliable data on the load-bearing capacity of the soil. Whether these surveys are based on the low-cost, time-saving driving method, on costly test borings or on chemical soil analysis must be decided for each individual case. Work of this type is also carried out by specialized firms who have the necessary equipment.

Development survey

Where infrastructure is required such as site grading and access roads (e.g. to mountain or desert stations, but also along cable routes) a survey for the development of the proposed site areas is useful and sometimes unavoidable. Consideration should be given to limiting the slope of access roads and to the risk of flooding, and provision should be made where necessary for alternative access or for safeguarding the primary access route. In a straight cost comparison, this can result in the downgrading of a site which is otherwise ideal with respect to propagation. The development survey is particularly important in providing data for estimating the cost of anticipated construction work.

Survey team equipment

This brief outline of the various survey types and their individual objectives demonstrates that the desired results can only be achieved by a well-prepared, experienced survey team with the necessary equipment.

In many cases the results of the survey are crucial for the subsequent positive or negative progress of the project as well as for the reliability and easy maintenance of the links.

The equipment of a survey team nowadays includes:

- the entire range of surveying instruments, such as theodolites, distance meters, precision altimeters etc.;
- satellite navigation devices for accurate position-fixing in unmapped areas;
- telephone sets for mobile use in order to "keep in touch" when working in difficult terrain;
- mobile equipment including crank-operated masts and generators for carrying out propagation tests;
- self-contained, recording-type environmental instrumentation for long-term acquisition of climatic data as a planning aid for power supplies (e.g. solar or wind systems);
- mobile test vehicles for propagation testing in mobile radio networks.

Optimizing the planned route

As previously explained, the reliability, smooth installation and subsequent operation of a network as well as its

maintenance are directly related to the optimization tasks of project planning. Cost and technology must be balanced, taking local conditions into account. If the tailored project mentioned at the outset is to be realized, these aspects of optimization must be kept in mind at all times – from deciding the network structure, preparing and carrying out the survey, through to the final planning of the networks, links and stations.

In order to achieve a "tailored" or "customized" project plan and prepare alternatives, it is necessary to include many factors in the planning process, such as the accumulated details about the network configuration, about traffic relations and their likely trend, about the ideas and requirements of the client and not least details about the relevant area, its climatological characteristics and the associated propagation mechanisms.

The final selection of transmission media, station sites and routing entails much comparison of planning and cost options, with the infrastructure options being no less crucial than transmission criteria. Indeed, the cost of access roads, buildings, towers, protective measures and construction work on cable routes is many times higher than that of the transmission equipment.

In densely populated areas there is usually a highly developed infrastructure to fall back on. In such cases, the routing should be adapted as far as possible to take advantage of this. Telecommunication towers in the landscape are a necessary evil, but should not be erected without regard for the environment or in excessive numbers.

In other areas the infrastructure must be created in the course of constructing the new links and this often involves crossing long stretches of sparsely populated terrain (desert, steppe). In these situations it is particularly important to choose suitable sites and self-contained station systems. In this respect, the cost of maintenance and operation should be considered when selecting systems and station equipment, particularly the power supply. Problems in the supply of fuel, water, etc. have caused many a link to become a liability. This is the main area of application for maintenance-free systems with regenerative power sources which obtain their primary energy from the sun and wind.

Buildings and shelters

Building and space planning forms a significant part of project planning activities. In new buildings and conversions the equipment rooms must be sized to allow for future expansion with a reasonable degree of certainty. In towns and large communities particularly, the subsequent expansion of equipment buildings can only be carried out at considerable cost; therefore, it is important to adopt a sufficiently long time scale at the outset. Predictive planning of this kind involves making certain assumptions as to new technologies and transmission media, wideband communication, broadband subscriber communications, etc.

As equipment continues to become smaller, heating and ventilation requirements involved in building and space planning become more exacting. The heat dissipated by equipment in confined spaces is such as to require ventilation systems even in normal climatic zones. Computer flooring (false flooring for ventilation and cabling) or rack suite ventilation, configuration and installation density are factors that must be balanced as part of the space planning activity. Even the cabling routes within a telecommunication office must be planned to avoid subsequent building work as far as possible. Wall openings and cable ladders are forever bottlenecks to expansion.

Old equipment buildings are often not adapted to the new specifications for floor loading, heat dissipation and room height. In such instances, the task for the planners is to find ways of locating the equipment so that it can be installed in as uncomplicated a manner as possible. Owing to the higher equipment concentrations, particular care should be exercised in designing ventilation facilities (e.g. incorporating ventilation plinths or double flooring).

Apart from the conventional style of equipment building there are various designs of shelter available particularly for radio relay stations. For ease of shipping the dimensions of these shelters should be restricted to the standard container sizes of 20 or 40 feet.

Shelter stations are particularly useful in sparsely populated and remote areas for the economic installation and maintenance advantages they confer. The design of the shelter and the facilities it incorporates depend on the climatic conditions on site and on the services available there. However, small station buildings of conventional design have also been used in some countries, particularly where there are import restrictions or local resources available at low cost. In either case, the choice is closely related to the requirements of the power supply system.

Not all countries have a stable and virtually interruption-free power distribution network. Many countries merely provide local networks of varying availability which is often too low to guarantee the reliability of the transmission systems. Problems in supplying fuel for diesel plants can be extremely serious in some countries. For this reason careful consideration of the technical options is required when selecting types of station. There is a direct relationship here between equipment power consumption and space requirement. Heating and cooling systems impose an additional load on the power supply and require special solutions such as passively cooled shelters.

With long experience of major projects and requirements in different countries, Siemens offers a wide selection of stations.

Stations with standby ac power plants

This type of station requires a highly reliable ac supply and is distinguished primarily by the high power rating available. It is able to supply transmission equipment operating at high transmitter output powers and nodes employing several transmission systems in different directions. In such a system air-conditioning or ventilation and/or heating of station rooms can be relied upon, even under extreme climatic conditions. Such stations are usually of conventional construction, for example, the standard building in Nigeria (**Fig. 4**) and concrete towers used by the Deutsche Bundespost, etc. However, containers with 20 or 40 foot shipping dimensions can also be used, with the standby ac power plant housed in a separate container.

Stations with diesel plants

In areas with no ac supply and for stations with heavy loads it is necessary to

Fig. 4 Radio relay station in Nigeria, Area 4, with standard building and 102.5 m high antenna tower

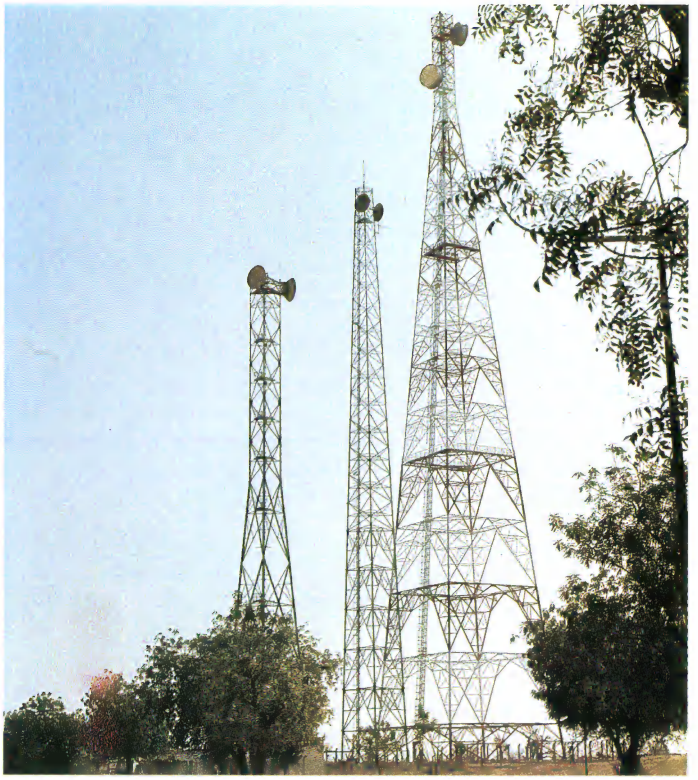

Fig. 5 Witnesses in steel to planning errors; the individual radio relay towers were not designed for subsequent expansion

provide self-contained diesel plants. Such plants are usually duplicated for reliability reasons and maintenance (double diesel and tank installation). The diesel plants must be rated to allow for subsequent expansion of the station to maximum capacity. At the same time, however, it is important to ensure that the diesel plants are operated close to their optimum loading.

In order to keep maintenance costs low, paths and sites should be selected to minimize stations with self-contained diesel plants. The dual diesel configuration means that the battery capacity is limited to a few hours. The buildings and containers for such stations are similar to those for stations with standby ac power plants.

Shelters with ac supply and storage cooler

For stations with access to a local ac supply which is subject to only occasional outages, there is a version of the shelter with battery backup and storage cooler for extracting heat dissipated by the equipment. A highly insulated shelter is able to accommodate small switching systems (e.g. digital EWSD concentrators) with the associated transmission facilities as well as equipment for other services dissipating up to about 1200 W. If the ac supply fails, the built-in storage cooler keeps the indoor temperature at the required levels to ensure reliable operation of the equipment even when outdoor temperatures are extreme. A mobile diesel plant can be readily connected in the event of a prolonged outage.

Shelters with solar plants and passive cooling

In areas where solar energy is readily available, shelter stations with solar systems rated up to about 500 W can be operated economically. For enhanced reliability the solar system is duplicated. The size of the solar and battery system depends on the solar energy available on site. Owing to the limited power, this type of station is restricted primarily to use on low-output-power radio relay repeater stations. Solar capacity and battery reserve must be calculated individually to suit the particular country. The heat dissipated by the transmission equipment is extracted via a passive cooling system exploiting the difference in temperature between day and night.

Shelters with solar and/or wind plants and passive cooling

In areas with adequate availability of wind and solar energy (e.g. desert and mountain regions), shelter stations rated up to about 1000 W can be employed economically [4]. The wind generator system supplements the solar system, making it possible to vary the ratio of wind to solar energy to suit regional conditions. As with the previous shelter, heat dissipated by the equipment is extracted via a passive cooling system.

Foundations, towers and soil conditions

On radio relay routes the selection and design of towers and antenna systems is an important aspect of project planning. Towers and masts should be designed to allow as far as possible for future expansion. If towers are designed for current capacity only, there will be a considerable additional expansion cost caused by the erection several towers on one site (**Fig. 5**).

Possible antenna supports are self-supporting tower structures and guyed masts, both of open-lattice steel design, and concrete towers. Each variant has its own particular advantages and disadvantages which must be considered in relation to each other when planning a radio relay route.

A *self-supporting tower* features high rigidity and low space requirement. This structure is so versatile that it meets virtually all transmission system requirements. However, as the height of the tower increases (from about 60 m) there is a noticeable increase in its weight compared with the guyed mast. In this respect, the *guyed mast* has a clear advantage in that it can usually be produced at lower cost owing to its reduced material requirement.

On the other hand, this structure also has crucial drawbacks. The large area it requires to accommodate the guying arrangements not only increases the real estate and security costs, but also restricts its application, particularly in mountainous regions and built-up areas. It can also only accommodate a limited number of antennas because of the limitations imposed by the guying arrangements. The most suitable corrosion protection for the steel construction is dip-galvanizing which, depending on the environment, will last for many years.

Concrete towers with or without equipment rooms at the top have a much higher initial cost than steel constructions. When these towers are designed with a platform, however, they provide space for a large number of radio relay systems. The maintenance costs due to environmental effects and corrosion are negligible. When properly designed concrete towers also fit more readily into the landscape, which is a factor in keeping with the heightened environmental awareness in many countries.

In order to ensure that a tower is stable, the construction must be anchored in a suitable *foundation*. The soil conditions encountered on site are a crucial factor in this respect since, in conjunction with the requirements of the support structure, they determine how the foundation is laid and its design. Unlike ordinary foundations, the tower foundation must absorb or transfer to the ground not only compressive forces but also considerable tensile forces and tilting moments from wind and antenna loading.

Foundations are almost universally of reinforced concrete. Sound and optimized load-bearing characteristics are essential in the construction of foundations. The type of foundation adopted depends on the soil conditions encountered and on the technical capabilities of local construction firms on site, as illustrated by an extreme example in **Fig. 6**.
A foundation frequently employed is the "pad and chimney" configuration (**Fig. 7**). With this design, the forces exerted by the tower through its legs are transferred via a "chimney" to the base laid 2 to 6 m deep. For towers with a small cross section, this involves all the legs being embedded in one foundation. For towers with a spread of more than 3 m, the foundation takes the form of a pad under each leg. As the forces transferred from the tower increase and the load-bearing capacity of the subsoil decreases, the size of the base must be increased. The "grillage" foundation with its shallow depth and simple form is particularly suitable for areas with weathered rock or sandy substratum.

Fig. 6 Laying tower foundations in an inaccessible mountain region

Fig. 7 Building a "pad and chimney" foundation in Nigeria

Fig. 8 PROCADIS graphic workstation for computer-aided planning of communication links and networks

However, the siting of the tower cannot always be based on soil-loading considerations and must take much more account of transmission factors. Hence, when extreme soil conditions are encountered, it is necessary to resort to special foundations forms. They are, however, highly cost-intensive and are only adopted after all sites and transmission options have been considered.

In marshy and swampy areas, deep foundations are required. Since the soil conditions will not support the load, concrete or steel piles are bored or driven into load-bearing strata. Such foundations are usually between 15 and 40 m deep. If the substratum is rock, it is possible to anchor the foundation on the rock bottom. The compressive forces from the tower are transferred via a relatively small foundation to the rock which permits very high surface compression. Tensile forces are absorbed via steel anchors let into the rock. This type of foundation, however, requires solid and little-fissured rock.

For both of the latter foundation types, it is advisable to verify by tensile tests that the piles or anchors are securely anchored in the substratum to ensure that the antenna support is stable. It is also important to ensure that chemically aggressive soil conditions do not lead to slow destruction of the foundations. With aggressive soils it is absolutely necessary to use special-purpose cement. It should also be ensured that foundation components can be reliably and readily incorporated in the station grounding network.

Application of modern computer planning systems

A fully developed and optimized project planning process is essential if the subsequent work is to be completed economically and smoothly. Incorrect deliveries and structural alterations due to planning mistakes cost time and money. These large-scale planning and optimization tasks are, therefore, hardly conceivable without the use of modern computer resources. At the same it should be kept in mind that construction documents must take account of the differing local conditions, the skills of the personnel and the capabilities of the construction firms. Language problems here can be overcome with the aid of diagrams.

For many years Siemens has endeavored to improve the planning aids for communication engineering and to increase the reliability of the planning results. The facilities employed include portable minicomputers with special survey and comparison programs as well as personal computers and graphic workstations. The recently introduced PROCADIS (project planning system, CADIS) with its graphics workstation (**Fig. 8**) connected to the BS2000 mainframe computer can be used to draw up plans quickly and reliably and, at the same time to define the parts to be supplied. The large memory in the BS2000 permits storage of the project plans and central monitoring of the information stored. Optimization calculations can be performed quickly. Route and network plans, which are known for their frequent alterations, can be continually updated and printed out at short notice.

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Bertram Brubach and Michael Glaue

Project Management for Communications Engineering Projects Abroad

In addition to precise technical planning, a vital necessity for any large-scale project is to set up an organization tailored to the needs of that project. Such an organization is a significant factor in the successful and economical management of a project and in ensuring client satisfaction. This applies most particularly to turnkey projects which involve not only installing the communication equipment but also entail a number of additional services (e.g. preparing new station sites, erecting antenna towers up to 160 m high and constructing access roads and station buildings).

Compared with large installations built on a single site, communications engineering projects, which often involve the installation of an extensive network of widely dispersed stations across an entire country, require complex management planning. Drawing upon experience gained in major projects undertaken by the Siemens Transmission Systems Division in recent years, the authors discuss the subjects of organization, personnel, administration and project infrastructure. They describe in detail what lies behind the term project management. The purely technical aspects of a project are only considered in passing.

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Management planning

Once the Division has decided to bid for a PTT turnkey project abroad, generally in response to an international invitation to tender, the *nature* and *scale* of the project management requirement must be planned and *costed* even before the tender is submitted. Depending on the size of a project, it is necessary to specify the project organization, to plan the site offices or support bases and in most cases to conduct a survey in the particular country. The purpose of the survey is not only to clarify technical questions but also to investigate transportation facilities, the ability to deploy local personnel and local subcontractors to provide certain services, the housing situation for personnel and available communication facilities.

Although in the course of its worldwide activities Siemens has built up a large amount of retrievable data on specific countries, there are still a large number of project-related questions that require further investigation in the country itself. The results of the survey are the basis for a more precise cost calculation of the wide range of individual items which fall under the general heading of *project management*.

Project organization

In order to be able to provide the contractually specified services in the particular country, it is necessary to set up a temporary organization which is considered to be a "subcontractor" operating like a separate profit center. This approach requires an organizational structure adapted to suit the contract with an appropriate division of activities and clearly defined responsibilities to ensure that the project proceeds smoothly. The organizational chart makes it clear to all involved exactly who is responsible for what and to whom that person is responsible. Overall responsibility is borne by the project manager who reports directly to the Division's *project planning* department in Munich.

Fig. 1 shows a basic organizational chart for a turnkey project with a single site office. A number of large-scale projects have been completed using this proven structure. If a project involves setting up several remotely located site offices with separate area project management teams, this chart is expanded accordingly under an *overall project management* organization with its headquarters close to the client's headquarters.

Deployment of personnel

Superiors and subordinates for the individual fields of activity in a project are selected and assigned by name to their jobs in accordance with the organizational chart. This manpower planning phase must be completed well in advance of the actual project begin and does not merely apply to specialists from the home office.

For example, the planning phase usually includes arranging for the possible release of staff from local Siemens branches or companies. By enlisting personnel from this wide range of sources, it is possible to deploy individual staff in a flexible manner, i.e. to match manpower levels to requirements as the project progresses.

One of the most difficult tasks during the planning phase is to find suitable project managers. First, they must be qualified engineers with the widest pos-

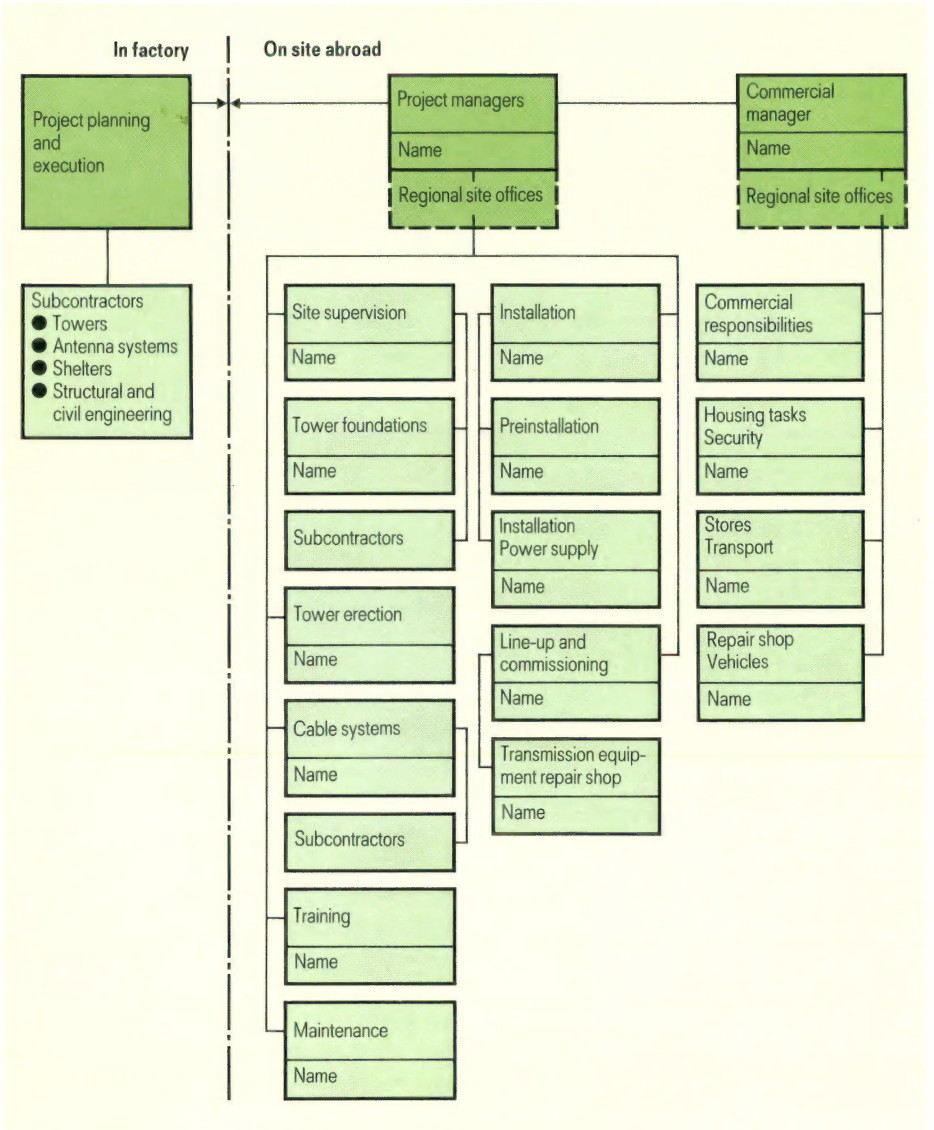

Fig. 1 Basic organizational chart for a turnkey communications project

sible range of professional experience, i.e. as well as having the necessary technical, commercial, organizational and personal leadership abilities, they must also be capable of managing the business interests of the Division abroad. Second, the candidates — most of them with families — must be prepared to be away from their familiar surroundings for several years. Once suitable candidates have been found and nominated, they must also be accepted by the client. Clearly, the image of a company is enhanced when the client has the impression that the company carrying out the project has appointed competent personnel for project management. The Transmission Systems Division has always been and will continue to be capable of providing the appropriate specialists for each project.

Project management

By virtue of the qualities mentioned above, the project managers are able to make on-the-spot decisions affecting the success of the project — often under difficult circumstances. Where certain action is proposed during the project which could have repercussions in the technical, commercial or sales/marketing areas, the project management consults with the relevant departments of head office. For example, completion deadlines affecting the head office in terms of equipment delivery, document preparation or the dispatch of personnel are decided upon jointly during the project. For the project managers on location, this means converting the respective agreements into detailed planning schedules (e.g. harmonizing the deadlines for building construction, installation work, transportation and housing the provision of financial means).

For, whatever the decision, it is ultimately their responsibility to manage the project economically (cost-effectively) and to provide all the goods and services specified in the contract on time and in perfect condition to the complete satisfaction of the client.

If contact between on-site project managers and the project planning department in Munich is temporarily lost due to communication equipment failure, the project managers must keep the project moving forward even without support from the home office.

Moreover, the project management is held *responsible for statements relating to the project* in correspondence, negotiations with the client and in presenting reports. The monthly reports are used to keep both the client and the head office departments informed about the progress of the project. In addition to these basic tasks, there are a number of other important subjects directly relevant to the project management's field of activity:

- *selecting subcontractors,* i.e. calling for and comparing bids and awarding contracts;
- *constant contact* with the client, his consultants or other companies which are involved in the completion of the same project;
- *checking* whether the contractual commitments are being met both on the project side and on the client's side;
- *manpower planning* and *employee welfare* in work-related or private matters as well as providing *instruction* in health care and job safety;
- *representing* the Division or even the Company as a whole whenever the occasion arises – because, as mentioned above, the project managers and indeed each individual employee involved in the project are shaping the corporate image in the eyes of the customer and the public at large.

In the commercial sector, the project managers are fully responsible for *keeping within the budgeted cost limits.* It is therefore necessary to maintain site cashier's offices which also provide information on the current state of income and expenditure for the project.

In addition, the project managers have the responsibility of *arranging for contractual payments to be made by the client*. For this purpose, it is necessary to produce evidence of work carried out or deliveries made, to raise invoices and submit them for inspection by the customer before payments can be effected.

In order to ensure that projects abroad are completed on schedule, it is vital that *import licences, customs clearances* as well as *residence and work permits* for expatriates *are obtained without delay*. This is the project managers' first priority before the project commences. The documents are usually obtained by the contracter from the various government offices with the assistance of the client in the particular country.

The above project management duties described are the most important ones and should convey an impression of the variety of subjects involved in projects abroad.

Fig. 2 Site office complex in northern Nigeria including offices for project management, storage areas for equipment and materials, various workshops and a preinstallation area

Site offices

In order to ensure that large-scale projects are managed efficiently and cost-effectively, it is extremely important to provide optimum working conditions for the personnel. This includes *site offices* (**Fig. 2**) which are suitably partitioned and equipped for the various technical or commercial groups and adapted to suit the geographical conditions of the project. On many contracts abroad, the project workforce is provided housing by the local Siemens agency; in other cases, the project managers must first rent site offices or arrange for new buildings to be constructed.

A site office complex comprises not only *office rooms,* but also an *open-air storage area* for tower materials and tanks, a *warehouse* for equipment with a *preinstallation department* and, if required, a *vehicle workshop* with gas station. In Nigeria, for example, it was also necessary to set up a *carpentry,* a *mechanics* and an *air-conditioning workshop*.

To save time and money, it has proved useful to set up a preinstallation department in the site office area (**Fig. 3**). This enables transmission equipment to be assembled, cabled and aligned efficiently for each station on an "assembly line" system. In certain countries centralized preinstallation offers additional advantages because it minimizes the time spent by the technicians at remote stations (e.g. in the bush or desert). Furthermore, the central preinstallation shops can also be used for on-the-job training of the local Siemens personnel or the client's operating staff.

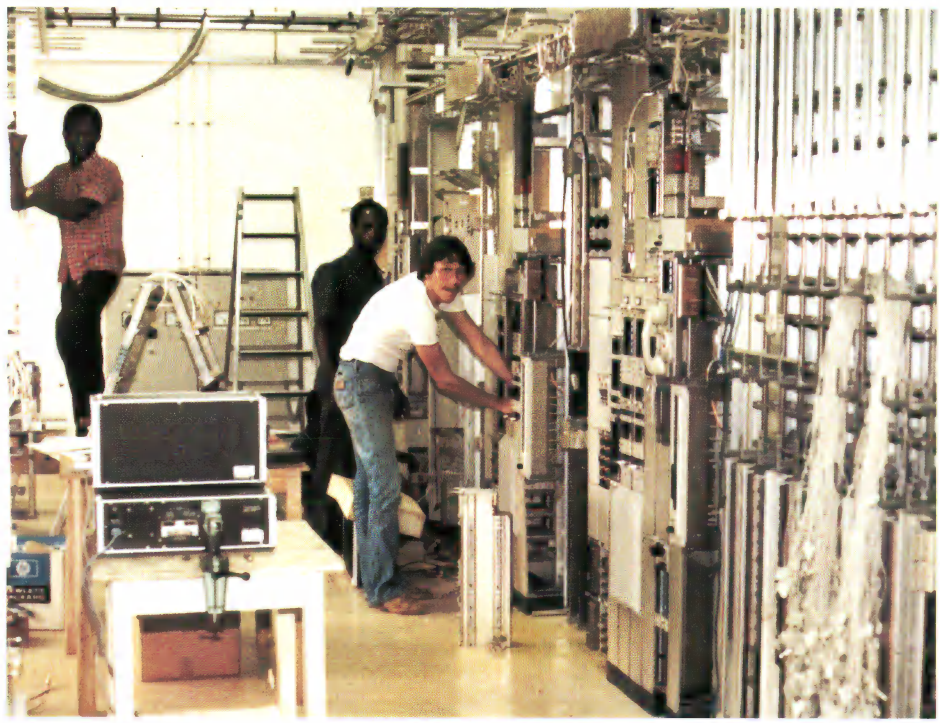

Fig. 3 Preinstallation department on site where certain components are preinstalled and tested before being transported to the remote installation site

The infrastructure of a site office comprises not only the *water supply* (relying sometimes only on its own well or tanker deliveries) and *electricity supply* (often only available from its own generators), but also the *communication facilities* such as telephone, telex and shortwave radio equipment. In countries where the communication facilities for long-haul and local networks are only just being put into operation, HF radio is often the

Fig. 4 Materials being transported by helicopter to a remote station in the Sultanate of Oman

Fig. 5 Transporting towers in bolsters by hired trucks from the port to intermediate storage sites in Benin, Nigeria

only means of maintaining contact between the site office and a remote station under construction or between a number of site offices.

It invariably happens that the contractor must also take account of unforeseen additional client requirements with respect to deadlines or rerouting during the construction phase, even though this temporarily disrupts project schedules. In such cases, the site offices must modify or provide new construction documentation on the spot. The contract documentation is then generally revised at head office (alterations to the contract) and subsequently submitted to the customer for approval.

Transportation facilities

The term *communication network* implies *expanse, spanning of distances, transportation logistics* and *mileage*. Depending on the size of a project and the country in question, it may be necessary to put special emphasis on the transportation facilities.

By far the most important requirement for setting up a network to schedule is *staff mobility* and an *efficient transport organization* for delivering the building materials and electronic equipment to remotely located stations. Employees who have to work in the field are provided with cars which are also suitable for transporting small materials, tools and test equipment. Trucks owned or hired by Siemens are used for moving material and equipment assuming these facilities are available in a country.

In Oman and Indonesia it was even necessary to use ships and helicopters for transporting men and materials to remote stations on islands or mountains (**Fig. 4**). For the major project in Nigeria, some 1200 container-loads of equipment and about 10,000 tons of steel for the towers were transported from the port of arrival to the transit depots inland using hired trucks (**Fig. 5**). The goods were then forwarded on to the stations as and when required using fleet trucks. This approach prevented materials being lost due to being stored for too long at the stations; it also enabled delivery schedules to be varied to suit construction progress.

By using *containers* and *bolsters* (open containers for the tower sections), the time required for customs clearance, port storage and loading/unloading of the trucks are minimized, and losses or damage in transit are virtually eliminated.

On some projects, containers purchased second-hand have proved extremely useful. After serving the purpose for which they were designed, they were placed at stations during the construction phase and used as site sheds for storing equipment and materials. These containers were then resold to interested parties.

Housing

At the start of a project, one of the most important administrative tasks is to locate or provide *personnel housing* or to rent entire camps if there is a comparatively large concentration of staff at

a single location. Very often the infrastructure in certain countries fails to meet the project requirements; for example, water and power supply failures are not uncommon in some countries. In such cases, each house must be provided with an *emergency power generator* and additional *water storage tanks* on the plot, which are replenished two or three times a week.

Camps have the advantage that the emergency and additional facilities can be installed centrally, but with correspondingly large capacities. In order to maintain the apartments, houses or offices, teams of workers (local personnel) with all-round skills are set up to deal immediately with any defects. For example, a faulty air-conditioning system can seriously inconvenience an employee staying in tropical latitudes and can undoubtedly have a negative effect on his work.

In countries with few hotels outside the larger towns, it is necessary to procure and furnish guest apartments or houses throughout the country on a temporary basis. In very remote regions it is necessary to provide containerized housing in so-called base camps. From these bases, personnel can drive out to the transmission network stations under construction. When activities are completed within a region, the living quarters can be disassembled or the containerized housing moved on to another site.

Personnel welfare

Not every country is a "tourist country" which provides a wide variety of leisure activities and which every employee engaged in foreign business is keen to visit. More often than not, large-scale or turnkey projects are located in countries offering only limited recreational facilities for Europeans. In such cases it is necessary, as part of *personnel welfare provision* and where finances permit, to organize and provide facilities such as *club rooms, tennis courts, swimming pools etc.* in camps, or to obtain permission to share the *existing recreational facilities* of friendly companies. The video cassettes of home TV programs, compiled by colleagues at the head office for circulation, are also extremely popular and enable contact with home to be maintained even in "the remotest corners of the world."

All this is vital for motivation, especially when the environmental conditions in foreign countries or the pressures of work impose severe limitations and require much personal engagement on the part of Siemens' staff.

Personnel welfare means not only meeting a new arrival at the airport in a foreign country but of course also *providing support in times of personal problems or difficulties,* as well as handling or assisting with formalities. Advice on *health precautions* and local conditions and peculiarities as well as on job safety are provided as a matter of course. Because the worksites (stations) in a transmission network are widely dispersed, lists of doctors' addresses, hospitals and branches of associated companies in the respective country are compiled in order to assist Siemens employees in emergencies.

Conclusion

Optimum solutions for all aspects of *project management* described above and, of course, technical expertise are essential to complete projects successfully and to ensure the client's favorable impression of the company. Further contracts are very much dependent on these factors.

From experience gained on several large-scale projects of different kinds, the Transmission Systems Division is always able to provide the right project management capability to suit each communication project both now and in the future.

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Path and Frequency Planning for Radio Relay Networks

The transmission quality objective and the availability of each radio relay link must be achieved with maximum frequency economy and minimum equipment cost. At the same time, account must be taken of the individual effects of routing, climate, topography, frequency band and equipment. As path and frequency planning are inextricably linked, two important planning steps are implemented jointly in order to strike the optimum balance between transmission quality and frequency band utilization, namely antenna site selection and path profiling. This forms the basis for determining the antenna heights and sizes, the transmission quality and availability of the link as well as any improvements necessary – e.g. larger antennas, diversity, adaptive equalization. The purpose of frequency planning is to provide the desired transmission quality using the minimum number of frequencies. The criterion for this is the ratio of wanted to interference power at the receiving site and is influenced by such factors as the radiation pattern of the antennas, the terrain and the output powers of interfering transmitters and their distance from the relevant receiver. This article describes a computer-based approach to planning radio relay networks.

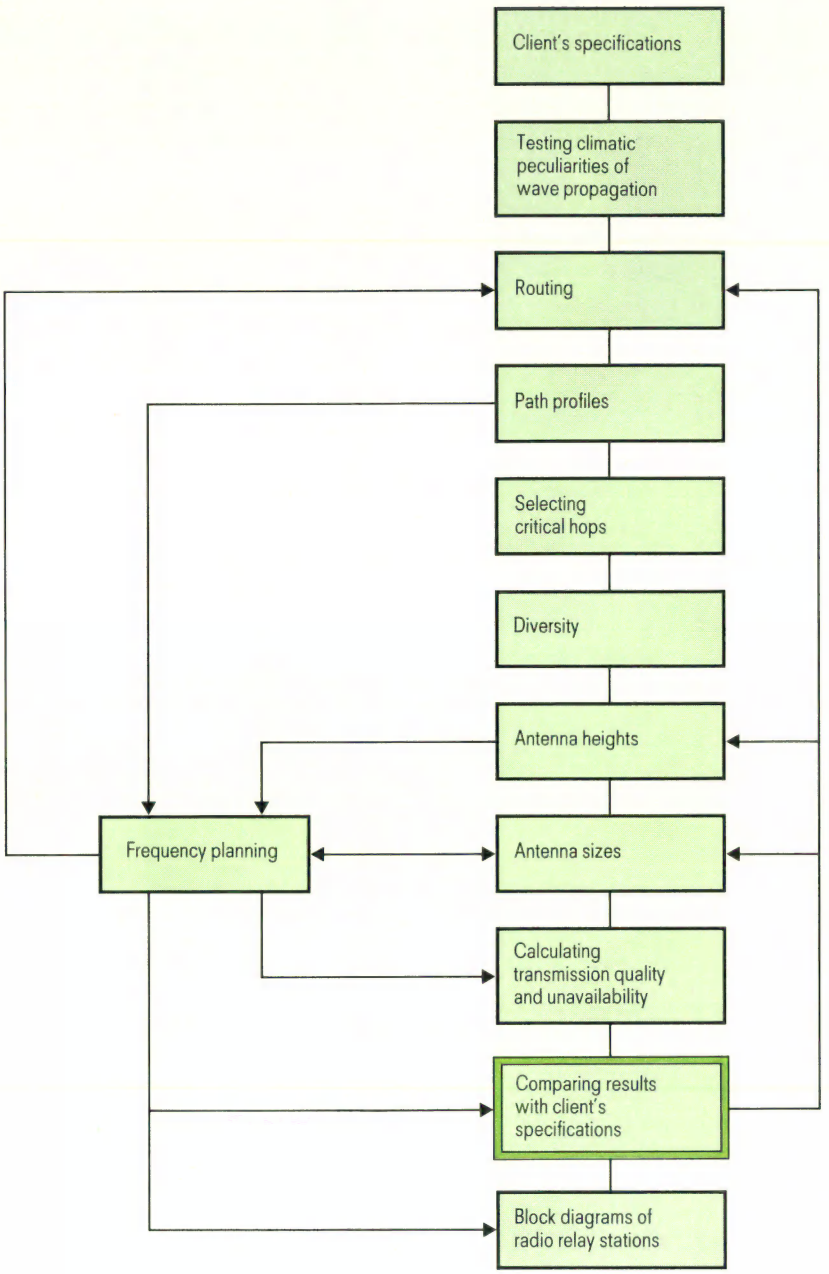

Fig. 1 The various steps in planning radio relay networks and their interrelationships

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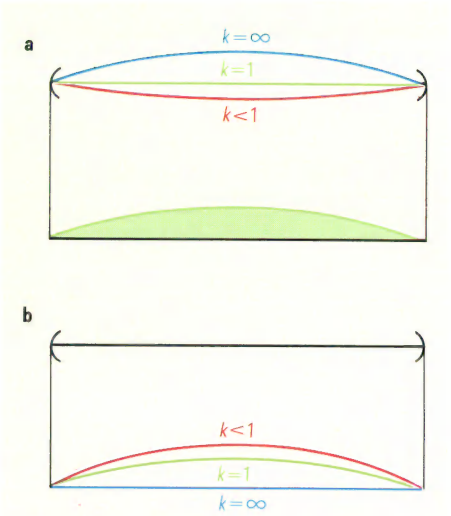


k Relationship of ray path curvature to true earth curvature

Fig. 2 Actual path of the ray in the atmosphere (a) and equivalent representation with straight-line ray path (b)

When planning radio relay networks, it is advisable to use a step-by-step approach, as shown in **Fig. 1**. The basic planning steps are executed interactively with a computer. The arrows indicate possible influences: for example, the frequency planning result may lead to rerouting; or hop lengths and routing will have to be modified if the desired transmission quality is not achieved using the assumed antenna sizes and heights. Planning is additionally influenced by whatever towers are available, antenna mounting options, existing radio relay links or satellite earth stations, etc. In view of these complex relationships, it is generally only possible to find cost-effective solutions by iterative calculations. These can be speeded up considerably by employing software specially developed for path and frequency planning.

Topographical and climatic effects on wave propagation

The most important factors affecting propagation in the frequency bands used by radio relay systems are:

- loss due to diffraction around obstacles on the earth's surface (terrain elevations, buildings) caused by variations in atmospheric refraction;
- selective fading and depolarization due to multipath propagation (reflection from the ground, water surfaces, buildings and layers occurring intermittently in the atmosphere);
- attenuation and depolarization due to precipitation (mainly at radio frequencies greater than 10 GHz).

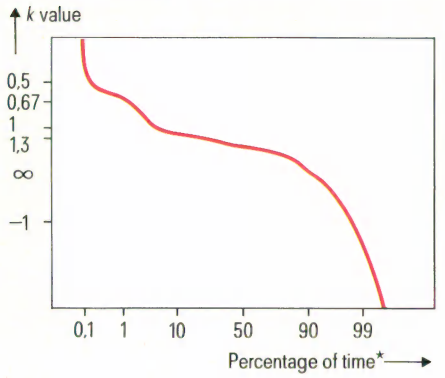
Diffraction loss

With normal hop lengths and climatic conditions, attenuation due to diffraction around obstacles can be largely eliminated provided the antenna heights are established on the basis of a path profile meeting the following criteria:

- 100% of first Fresnel zone is clear given normal refraction ($k_{50\%}$),
- 30% of first Fresnel zone is clear given unfavorable refraction ($k_{0.1\%}$).

The k value is the effective earth radius factor which relates curvature of the ray path to the true earth radius. It is calculated from the measured refractive-index gradient ΔN corresponding to the difference between the refractive index at a height of 1 km and that at a height of 100 m above the ground [1].

The effect of different k values on the ray path relative to the earth's curvature is shown schematically in **Fig. 2**. Normally the atmospheric refraction, and hence the effective earth radius factor, are subject to variations depending on the measuring site, the time of day, the season and, in particular, the weather conditions (temperature, humidity, barometric pressure). CCIR Report 563 gives worldwide distributions of the mean ΔN values [2]. The resultant effective earth radius factor $k_{50\%}$ for temperate climatic zones is approximately 4/3. Each location on earth has a specific k value profile according to the percentages of time for which k deviates from a certain value. This is shown in **Fig. 3** with reference to Jakarta [3].



* Percentage of the time in which k deviates from a given value

Fig. 3 Temporal distribution of the mean k value over a five-year period (example: Jakarta)

If these data are not available for a particular location, the planning may be based on the refraction distribution for a continental temperate climate and a 60% instead of 30% Fresnel clearance in tropical regions (**Fig. 4**). In desert regions, measurements are necessary in many cases because ducts and therefore

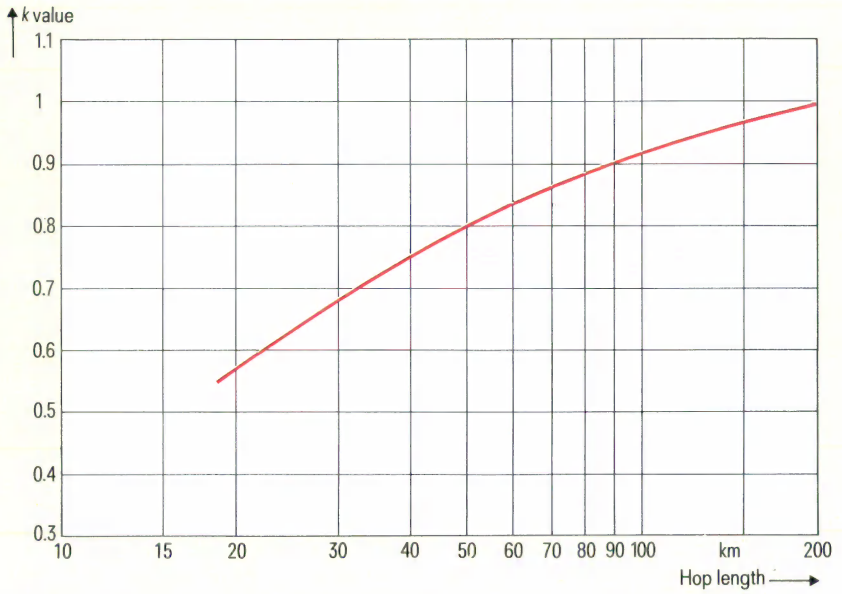


Fig. 4 Effective k value on a radio hop for 0.1% of the time during the worst month of the year (for a continental temperate climate)

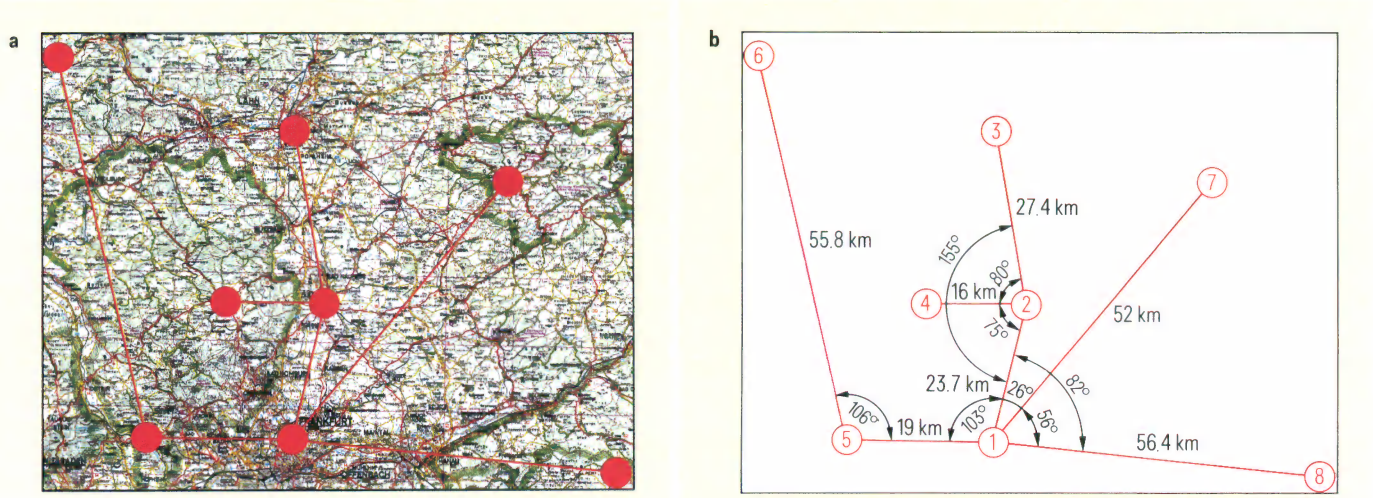


Fig. 5 The radio relay network is laid out by marking the stations on a map (a) and by computer-generated network configuration (b)

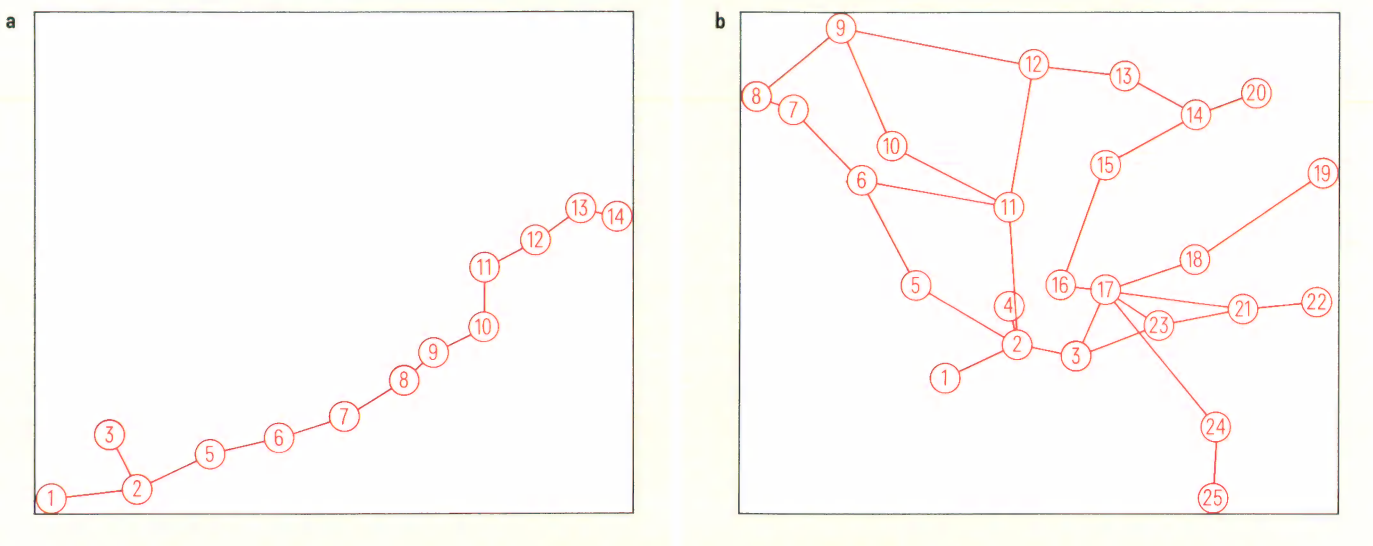


Fig. 6 Radio link in linear (a) and interconnected configuration (b)

overreach interference or heavy attenuation may occur due to severe discontinuities in the atmospheric refractive index.

If an unobstructed line-of-sight cannot be obtained, diffraction loss occurs which must be taken into account when calculating link outage times.

Multipath propagation

Multipath propagation via permanent reflection points

Smooth terrain with sparse vegetation and water surfaces causes echo signals and ground reflections which do not add in-phase to the main signal due to their longer delay time and may produce dispersive fading. Terrain of this kind must therefore be identified and pinpointed on the path profile. The antenna height is varied in order to move the critical reflection point to less reflective terrain. If this is unsuccessful, space diversity is employed. The optimum antenna heights and spacings can be calculated using a special computer program.

Multipath propagation via atmospheric layers

Multipath propagation via atmospheric layers is the major cause of short-term outages on radio relay hops. It not only produces deep fades (attenuation), but also amplitude and delay dispersion (distortion).

Measures to counteract the effects of multipath propagation

When planning a path, damp regions and flat meadowland must be avoided. The inclination angle of the ray path must also be as large as possible. The fading rate can be calculated on the basis of the criteria detailed in CCIR Report 338 (path length, frequency, terrain roughness, climate) [4]. Substantial improvements can be achieved by using space diversity, frequency diversity (also N + 1 protection switching over several hops) and, in the case of wideband digital systems, adaptive equalization. An extensive computer program is necessary to convert the diverse path parameters and the improvements obtained in

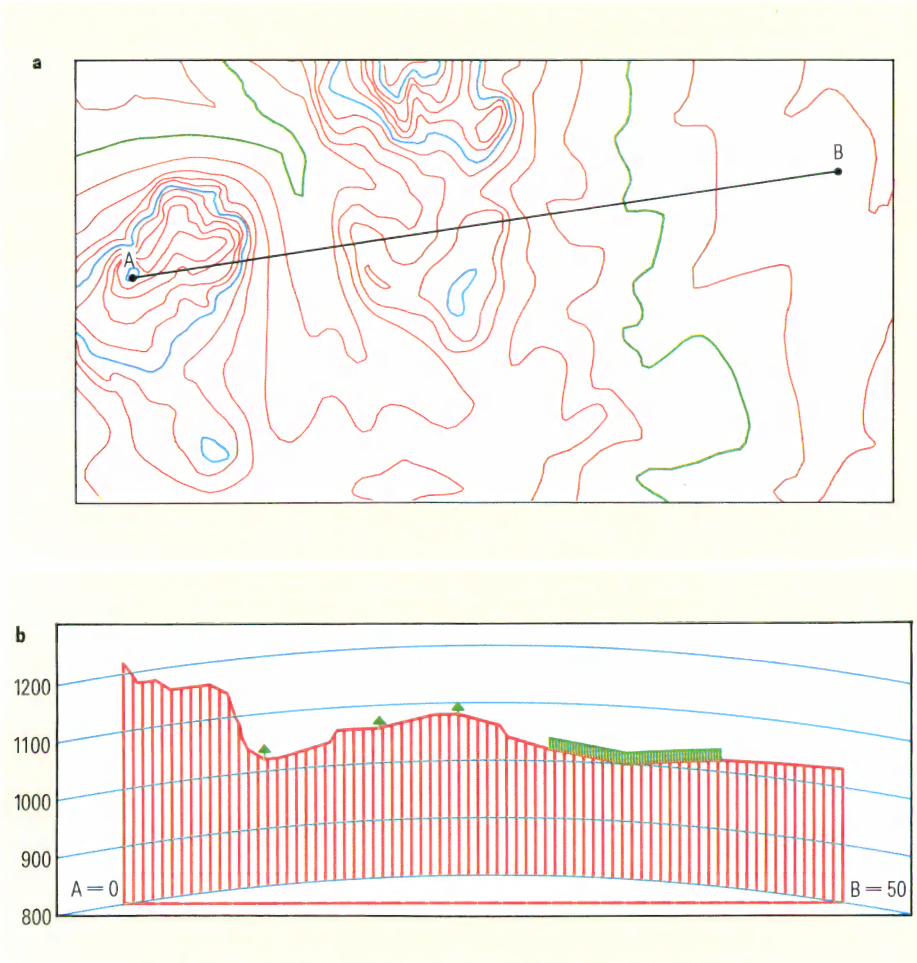


Fig. 7 Computer-aided topographical diagram (a) and resultant path profile (b)

previous runs into cost-effective solutions meeting the transmission quality objectives. Depolarization is another effect of multipath propagation that must be taken into account in frequency planning.

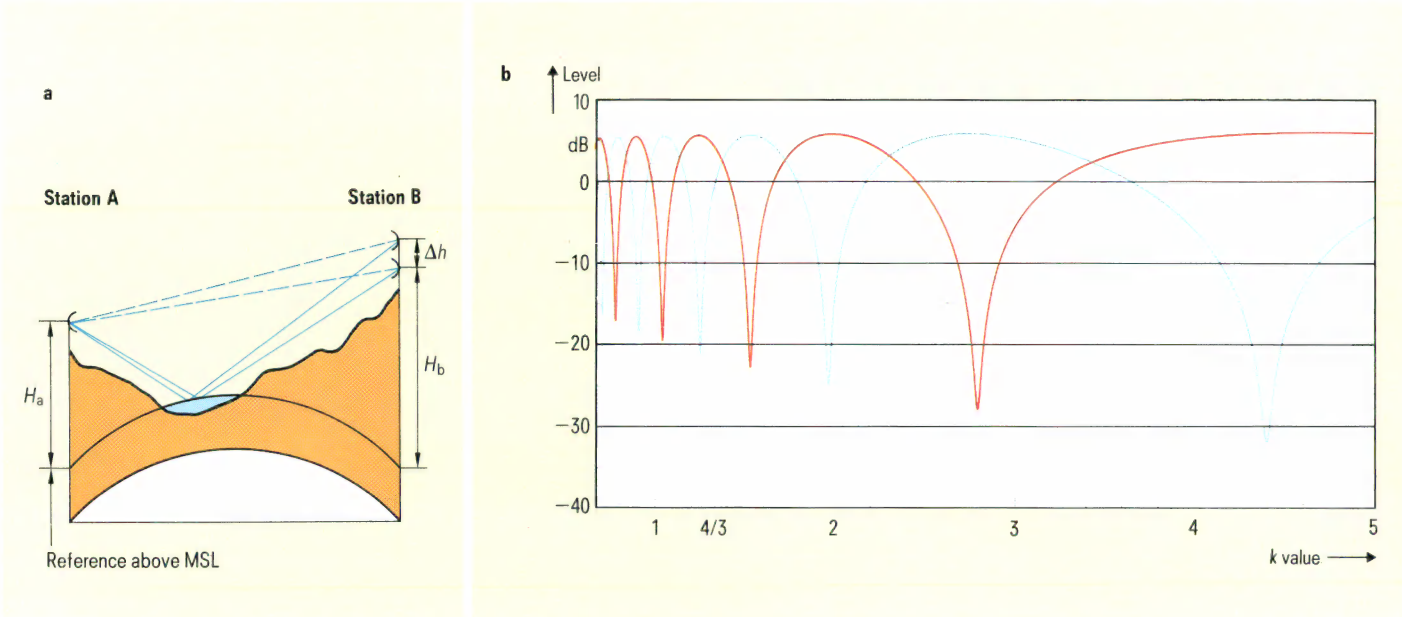
Rain attenuation

Heavy rainfall can result in prolonged attenuation or outages at radio frequencies above 10 GHz. The duration and frequency of the rain attenuation are primarily determined by the climate; the effect of routing is minimal (avoidance of barrier effects). For optimization purposes, it is possible to vary the antenna size, hop length and transmitter output power.

The computer program used is based on the calculation methods proposed in CCIR Report 338. The required frequency distribution of the rain intensity is obtained either from measurements or from the data collected for the various rain climatic zones detailed in CCIR Report 563 [2].

Routing

Transmission quality and availability are essentially determined by the geographical location of the radio stations. When



Δh	Spacing of receiving antennas of station B	Hop 1: From point A (400 m above MSL) to point B (650 m above MSL)	H_A = 61.5 m above gound
$H_{A,B}$	Height of operating antenna above reflection layer for stations A and B	Reflection surface: 200 m above MSL	H_B = 61.5 m above ground
k	Relationship of ray path curvature to true earth curvature	Hop length: 50 km	Δh = 10.4 m
		Frequency: 8 GHz	MSL mean sea level
		Roughness: 0 m	—— Operating antenna
			--- Diversity antenna

Fig. 8 Schematic representation of a ground reflection (a) and receive level with space diversity (b)

optimizing the transmission parameters and considering the economics of a radio relay network, it is also necessary to take account of a large number of additional factors, which include transmission capacity, type of signal, climate, type of terrain and any existing radio links. With these factors in mind, the first step is to select the radio frequency band and a suitable equipment system permitting maximum hop lengths for the planned tower heights and antenna sizes. Tentative radio station sites are selected on the basis of general frequency planning rules (e.g. upper/lower half band alternation, zig-zag routing, etc.), national frequency planning, possible connection to existing communication systems and the incorporation of available radio masts, roads, etc. In addition, the costs of the various solutions are carefully considered. Then, the radio relay stations of the preferred solution are plotted on a map (**Fig. 5a**), and their coordinates fed into a digitizer or directly entered and stored on a computer. After the stations have been assigned to their respective links, these data provide the routing diagram used for subsequent project planning (**Fig. 5b**).

Path profiles

Path profiles are required both for determining the antenna heights and towers and for frequency planning, particularly in the event of overreach propagation. If a radio link has an extended linear configuration (**Fig. 6a**), it is usual to enter in the computer only the values of contour lines intersecting the straight lines drawn between the stations. With a highly interconnected network (**Fig. 6b**), however, it is advisable to scan and store all the contour lines of the relevant map with the aid of the digitizer, as it is necessary to examine the possible interference between a large number of stations for the purposes of frequency planning.

Fig. 7a shows the contour lines extracted from a map and **Fig. 7b** the resultant computer-generated path profile including the type of surface (forest).

Selecting and evaluating critical hops

The most important criteria for identifying critical hops from their path profiles and the map are as follows:

- radio frequency, hop length, transmission capacity;
- "roughness" of the terrain, buildings, vegetation, water, damp regions;
- off-path obstacles or reflection points;
- climatic conditions, k value distribution, radio path following river valleys or running parallel to the coast;
- topography, inclination angle of the ray path (high-low hops);
- large clearance between ground and ray path (high-high hops);
- U-shaped path profiles (multiple reflections).

Diversity reception

Reception of the same wanted signal via two (or more) paths or on two frequencies is a proven method of preventing propagation-related interruptions and enhancing transmission quality. *Space diversity* is a technique whereby physically separated antennas are provided for receiving the signal on the same radio frequency. With *frequency diversity*, transmitters operating on different frequencies emit the wanted signal from the same antenna. A combination of the two methods is also possible *(hybrid diversity)*.

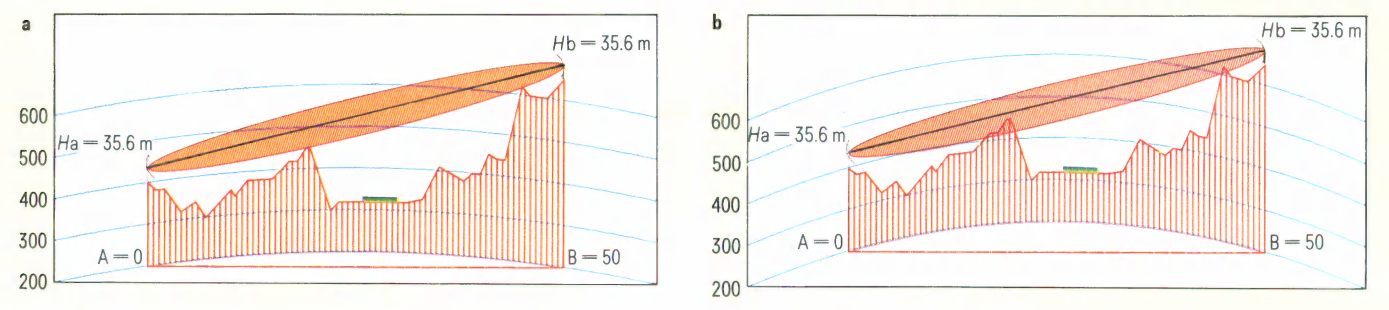
A computer program enables the planner to calculate the optimum antenna spacings or the required spacings between frequencies quickly and – if necessary – repeatedly and to present the results as curves. The input variables are the radio frequency, the hop length, the heights of the operating antennas, climatic effects and the nature of the ground.

An important aspect of planning is to limit the effect of ground reflections on the received signal. By way of example, **Fig. 8a** shows the diagram of a radio hop with ground reflections and two receiving antennas. Their spacing Δh is designed for the most frequently occurring k value. Ideally, all the level maxima of one antenna should coincide with the level minima of the other. A computer-generated graph of the type shown in **Fig. 8b** is used to check the adequacy of the diversity effect for other k values.

Determining the antenna height above ground (tower heights)

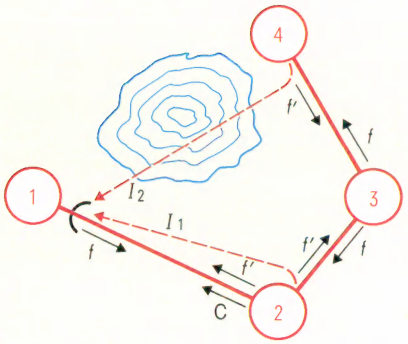
Critical radio hops are first examined to ascertain whether diversity is necessary. When determining antenna heights above ground the following variables are taken into account:

- type of path profile,
- radio frequency,
- k value distribution,
- antenna mounting options,
- tower costs as a function of tower height,



$H_{A,B}$ Height of operating antenna above reflection layer for stations A and B

Fig. 9 Effect of refraction (k value) on propagation under free-space propagation (a) and obstructed propagation (b)



C Wanted carrier signal
I Cochannel interference

Fig. 10 Diagram of interference in a radio relay network comprising stations 1 to 4; the isolation in station 1 is $C/(I_1+I_2)$

- overreach propagation in the case of cochannel operation,
- conformance with the antenna heights of adjacent hops.

The computer is used interactively to find the optimum solution for each hop by iterative calculations.

As mentioned earlier, the antenna heights are generally selected so that the first Fresnel zone (red ellipse) is clear of obstacles for the most frequently occurring *k* value. This is referred to as *free-space propagation of radio waves* (**Fig. 9a**). If smaller *k* values also frequently occur, it is necessary to check whether the additional loss due to obstruction is tolerable or whether it must be remedied by increasing the antenna heights (**Fig. 9b**).

Antenna sizes

As a starting point, the antennas are selected in accordance with the following criteria:

- radio frequency,
- gain,
- polarization,
- transmission bandwidth,
- wind load,
- tower stability,
- climatic conditions,
- costs.

Subsequent frequency planning and the calculation of transmission quality and propagation-related unavailability may

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PERFORMANCE CALCULATION OF DIGITAL RADIO RELAY - SYSTEMS

PROJEKT : AUSTRALIEN NEW-TWEED
PART A PATH - DATA

HOP Nr. / DISTANCE [KM]		1 / 21.1		2 / 35.6		3 /
HOP FROM STATION A TO STATION B		NEWCASTLE RAY.TERRACE		RAY.TERRACE GAN GAN		GAN GAN CABBAGE
		A	B	A	B	A
A.) SYSTEM DATA						
1. TYPE OF DIGITAL RADIO RELAY SYSTEM		DRS140/11.2ST		DRS 140/3900		DRS 14
2. CENTER FREQU. OF RF CHANNEL ARRANGEMENT	MHz	11200.0		3890.0		3890
3. BIT RATE	MBit/S	140.0		140.0		140
4. TYP OF MODULATION		16 QAM		16 QAM		16
5. TRANSMITTER OUTPUT POWER	Watt	1.0	1.0	1.0	1.0	1.0
6. RECEIVER NOISE FIGURE	dB	3.5	3.5	3.5	3.5	3.5
7. SYSTEM GAIN FOR BER 10 EXP - 3	dB	107.0	107.0	107.0	107.0	107.0
BER 10 EXP - 6	dB	102.5	102.5	102.5	102.5	102.5
B.) DATA OF ANTENNA SYSTEM (OPERATING ANT.)						
1 TYP AND DIMENSION OF ANTENNA						
1.1 PARABOLIC ANTENNA (DIAMETER)	M	3.7	3.7	3.7	3.7	3.7
1.2 ISOTROPIC GAIN	dB	50.0	50.0	41.0	41.0	41.0
1.3 HEIGHT ABOVE GROUND	M	50.0	50.0	50.0	50.0	50.0
H.) FADING - MARGINS						
1. 'FLAT'- FADING MARGIN BER 10 EXP - 3	dB	43.4	43.4	40.1	40.1	36.7
BER 10 EXP - 6	dB	38.9	38.9	35.6	35.6	32.2
1.1 INCLUDING EXTERNAL DEGRADATION	dB	3.0	3.0	3.0	3.0	3.0
2. DISPERSIVE MARGIN (INCLUD. EQUALIZER)						
BER 10 EXP - 3	dB	56.2		37.9		44
BER 10 EXP - 6	dB	53.2		34.9		41
2.1 IMPROVEMENT OF EQUALIZER	dB	20.0		8.5		21
K.) EXPECTED TOTAL PROBABILITY						
		DIRECT				
1. 'FLAT' + 'DISPERSIVE' BER EXP - 3						
WORST (FADE) MONTH OF THE YEAR A - B	%	.000040		.000004		.00
B - A	%	.000040		.000004		.00
2. 'FLAT' + 'DISPERSIVE' BER EXP - 6						
WORST (FADE) MONTH OF THE YEAR A - B	%	.002874		.000219		.00
B - A	%	.002874		.000219		.00

Fig. 11 Excerpts from a performance calculation for transmission quality and unavailability of digital radio relay systems

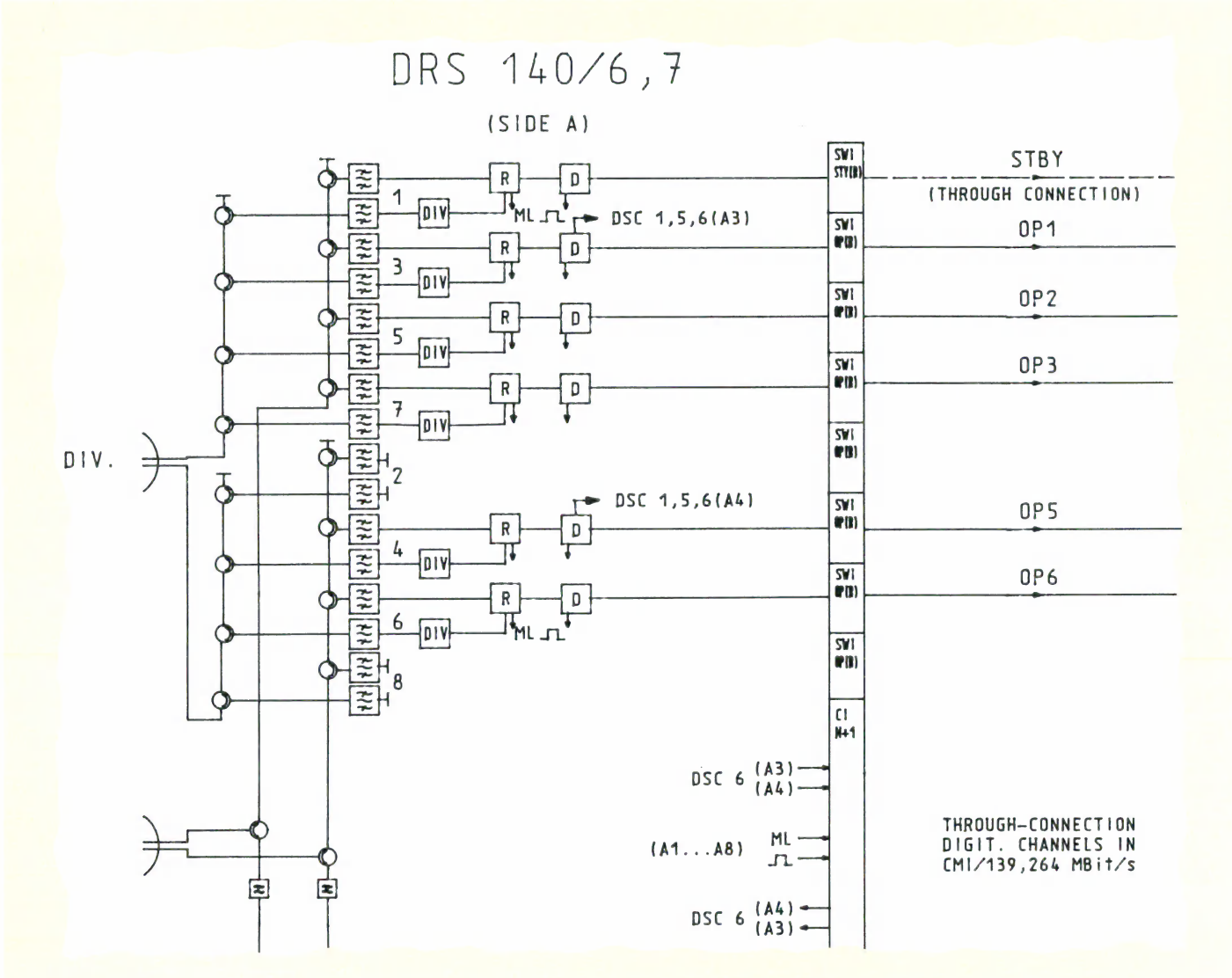

Fig. 12 Detail from a station functional diagram as produced by the computer

then lead to changes in the size or type of the antennas. In general, optimum transmission quality and economy are achieved only after several iterations.

Frequency planning

The purpose of frequency planning is to reuse the same radio frequencies as often as possible, while maintaining important parameters such as realizable antenna sizes, low interference and antenna system economy, and at the same time ensuring coordination not only with other radio relay, satellite and radar facilities but also with the networks of neighboring countries.

For frequency planning purposes, the radiation patterns of the antennas selected are converted to digital data using a digitizer and then stored in the computer together with the transmitter output powers, polarizations, frequency bands used, station coordinates, hop data, etc. These data are used to determine for each receiver the ratio $C/\Sigma I_j$ of the wanted carrier C to the sum of the cochannel interference powers I_j. This is illustrated in **Fig. 10** which shows three wanted signal paths each using identical frequencies f and f'. Additional losses due to terrain obstacles are taken into account in the calculation.

The objective for the $C/\Sigma I_j$ isolation ratio is 60 to 70 dB for analog transmission and 50 to 60 dB for digital transmission depending on the method of modulation. Inadequate isolation can be improved by means of more directive antennas, radio frequency (RF) attenuators, better utilization of terrain structure, different antenna heights, altering the polarization, changing the transmitter output power and the hop frequency assignment, or using other frequencies.

A special computer program enables calculations to be repeated rapidly and faultlessly with modified parameters. Without this assistance, these calculations would be extremely time-consuming as the number of interference relationships can be very large in an interconnected network.

Transmission quality and availability

Interruptions or interference on a radio relay link lasting less than 10 s, such as those caused primarily by multipath fading, are incorporated in the transmission

quality calculation in accordance with CCIR Recommendations 557 [5] and 594 [6]. Longer interruptions – mainly due to rain – are defined as unavailability. These calculations are used to verify that the planned radio relay link meets the requirements specified.

A complex DP program enables the computing times for result optimization to be kept within acceptable limits; among other things, it also allows the transmission characteristics of various radio relay systems to be compared. Its main input parameters are:

- equipment characteristics (transmitter output power, noise figure, etc.);
- type, height and gain of the antennas;
- feeder parameters (channel branching filters, waveguides, etc.);
- hop lengths;
- losses due to obstacles, diversity parameters (antenna or frequency spacings, etc.);
- propagation parameters (climate, terrain, etc.);
- path protection switching;
- frequency planning results.

Using these parameters, the program calculates the propagation-related transmission characteristics of individual hops as well as entire radio relay networks and produces the following results in tabular form:

Transmission quality of analog radio relay links (with multipath fading)

- Probability of exceeding a specified noise power (at least 10^6 pW) in the worst month of the year.
- Probability of exceeding the one-minute mean value of a specified noise power (usually 47,500 pW) in the worst month of the year.

Transmission quality of digital radio relay links (with multipath fading)

- Probability of exceeding a bit error ratio of 10^{-3} (one-second mean value) in the worst month of the year.
- Probability of exceeding a bit error ratio of 10^{-6} or 10^{-7} (one-minute mean value) in the worst month of the year.

Unavailability of analog and digital radio relay links (due to rain attenuation)

The unavailability is calculated for a 12-month period. For *analog* transmission, the limit value used in the calculation is a noise power of 10^6 pW or interruption. The corresponding criterion for *digital* transmission is a bit error ratio of 10^{-3} or an interruption.

Fig. 11 shows extracts from a typical computer printout. Having established this unavailability due to transmission medium effects, a separate computer program is used to determine the unavailability due to equipment failures.

Functional diagrams for radio relay stations

The final step in path and frequency planning is to present the equipment configurations of the radio relay stations in the form of functional diagrams; a detail from one such diagram is reproduced in **Fig. 12**. The equipment configurations form the basis for planning the mechanical design of the stations. A special computer-aided design (CAD) program helps the planner to reduce the time required to prepare these diagrams and to carry out any necessary modifications.

Summary

The computer-based method described here for planning radio relay links and networks can be used to find solutions for the most complex planning tasks. This has been demonstrated convincingly in the planning of a number of national networks (Philippines, Nigeria, Oman, Finland, Australia).

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Planning for Optimum Radio Coverage in Mobile Radio Networks

In a way similar to television and radio broadcasting, a public mobile radio system must provide adequate field strength for trouble-free reception to guarantee accessibility to mobile users throughout the entire service area. A central feature of the planning of mobile radio networks is the calculation of this *radio coverage*.

Radio coverage depends essentially on the structure (topography) and the surface characteristics (morphography) of the service area. These variables have an influence on the siting of the transmitters, transmitted powers, antenna radiation patterns, antenna heights, frequency reuse and, finally, the quality of reception.

With the aid of a recently developed procedure, both the contours depicting the topography of the land on maps and the enclosed areas of identical morphology can be scanned and stored in digital form. With the aid of a special computing procedure, path profiles are derived from these data and output via a plotter. The individual profiles enable the radio coverage of critical areas in particular to be recognized and to be considered in detail at the planning stage. The path profile data likewise form the basis for calculation of electrical field strengths as a function of the terrain and the distance from the fixed transmitter site. The calculated field strengths can be presented graphically under computer control as *ray diagrams*. By varying the transmitter sites, the transmitted power levels or the antenna radiation patterns, the radio coverage can be optimized by an iterative process.

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The topographic database

In order to establish a topographic database, geographical information is extracted from suitable maps showing the clearest possible contours and information relating to the terrain (unevenness, vegetation, buildings, lakes, rivers etc.) at the planning stage of a wide-area mobile radio network. The quantity and nature of the data scanned from the map and stored in digital form determine the organization of the data storage, the precision required of the computing program and the necessary computing time. For this reason, therefore, the file structure is dealt with first.

The topographic file

The contour structure of the entire service area is recorded independently of assigned transmitter sites or those to be subsequently determined. This approach ensures the greatest possible flexibility in defining and, where necessary, changing the transmitter sites. Such changes become necessary if the radio coverage of the service area exhibits *pockets* of insufficient received field strength, or if it is subsequently discovered that an existing transmitter mast does not have enough free space to accommodate the antennas. Once the topographic and corresponding morphographic data have been entered and stored, the path profiles radiating from any transmitter site can be calculated.

With the aid of a scanning device (digitizer), the analog structural data, contained on the map in the form of contour lines, can be quantized and converted into digital data. Maps with a scale of 1:50,000 and showing contour lines have proved ideal for this purpose and are available worldwide for the majority of countries. By entering reference points, the precise position of the map is defined on the scanning area of the digitizer, so that the geographical coordinates of each of its points are unambiguously defined. The height (above mean sea level) of the relevant contour is first entered digitally and then the entire length of this line is *tracked* with the aid of a scanning head containing a magnifying viewfinder with cross hairs. In this way, the complete sequence of geographical coordinates of the contour are stored in digital form in accordance with the selected quantizing step. The quantizing step suitable for a map scale of 1:50,000, for example, is 1 mm. This procedure is repeated for all the contours within the service area. For mountainous areas, where the contours are closely spaced, the scanning procedure can be accelerated by the selection of a few representative contours and subsequent interpolation. The sum of all the scanned coordinates is the topographic database.

The morphographic file

The nature of the terrain is indicated on the maps by areas of different color or shading. The boundaries of these areas are scanned in the same way as contours. A code number is also entered in the digitizer for each area to indicate the morphography of the enclosed terrain. Experience has shown that, for practical

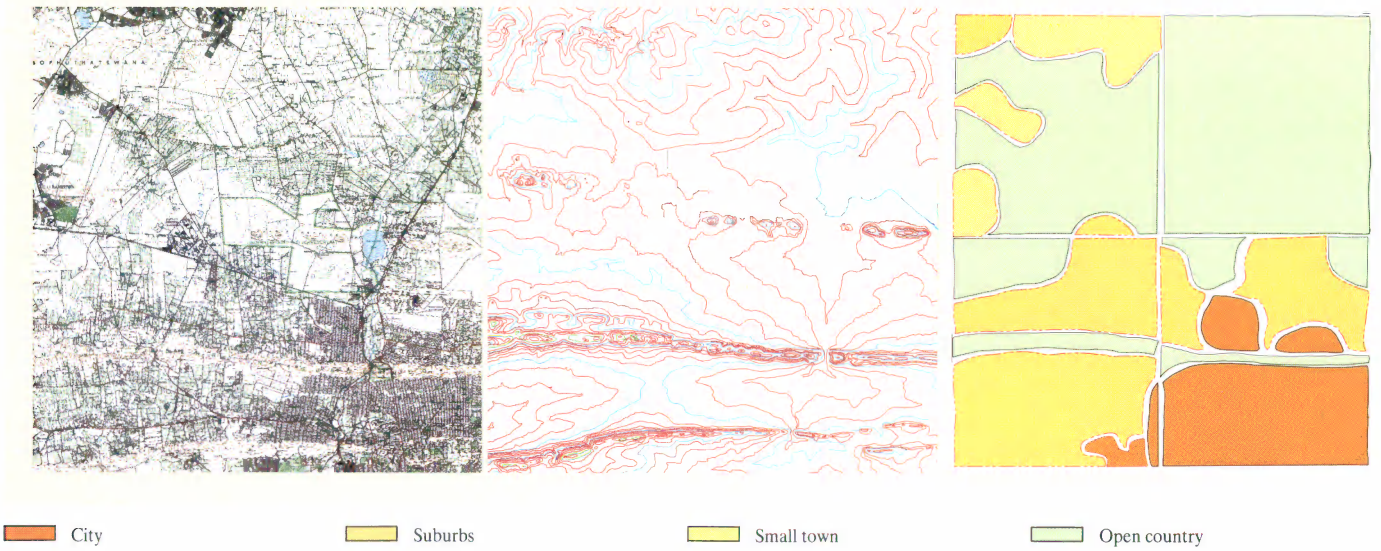

Fig. 1 Topographic and morphographic data recording
a Extract from original 1: 50,000 scale map **b Contour lines** **c Areas of identical morphography**

purposes, six different categories of terrain can be read from standard maps. These correspond to the map legends for cities, suburbs, small towns, open country, forest and water. The number of digital data records (coordinates) to be stored depends on the selected quantizing step.

Scanning results

With the aid of a plotter program, the contours and terrain boundaries can be drawn on acetate sheets, for example, with a plotter in order to check the input values and to allow comparison with the original map so that any input errors can be corrected.

Fig. 1 shows an example of the results of this data acquisition. **Fig. 1a** shows an extract from the original map, while **Fig. 1b** depicts the associated lines plotted from the scanned and digitized point coordinates of the contours, and **Fig. 1c** the boundaries of areas with the same surface characteristics recorded in a similar way.

Calculation of path profiles

The sites of the fixed transmitters (base stations) are either predetermined (if space is available on existing radio towers), or they are selected on the basis of suitable points on the map. Path profiles are then calculated around each site at selectable angular intervals and up to any radius. In this process, the data of all intersections along the path of each radial line with a contour are marked and their spot height and distance from the transmitter are stored. In calculating the path profile, the curvature of the Earth – the effect of which increases with the length of the radio path – and the diffraction of the radio beam in the atmosphere are accounted for by an Earth curvature factor k (e.g. $k = 4/3$).

Considering the quantity of data and the processing time required, a minimum profile interval of 2° is advisable. The 180 required profiles for a full circle do not, of course, completely cover the area surrounding a base station (at distances of 30 and 100 km from the transmitter, the tangential distance between possible intersections is about 1.0 and 3.1 km, respectively), but they are sufficient in number to allow analysis of the radio coverage of the service area and for evaluating the distance required between cochannel transmitters (reuse spacing) and their mutual interference.

In a corresponding calculation, profiles of the morphography are obtained from the previously recorded data. **Fig. 2** shows examples of a path profile and a

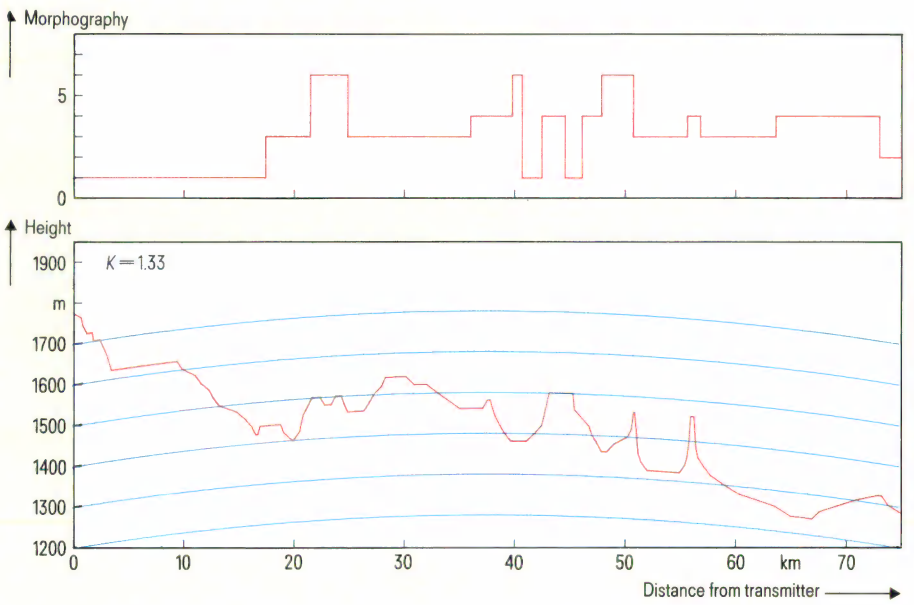

Fig. 2 Example of a plotted morphographic profile (above) and path profile (below)

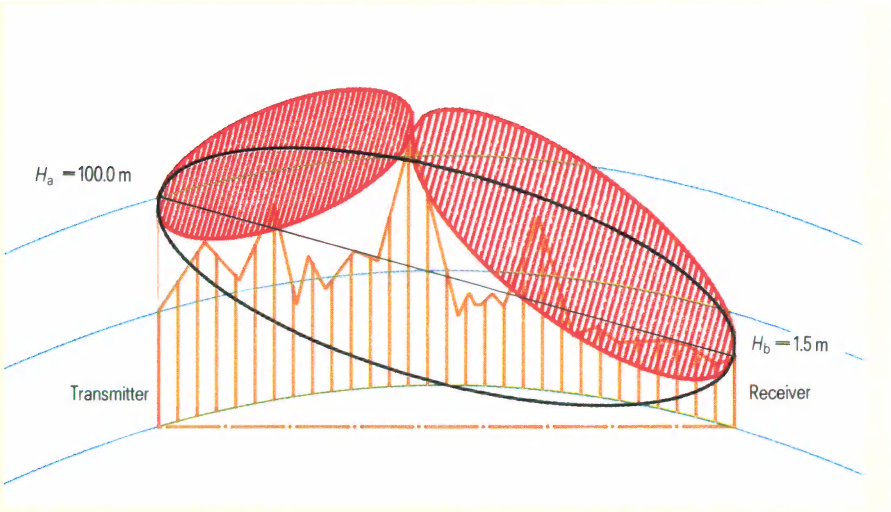

Fig. 3 Example of the calculation of total diffraction attenuation

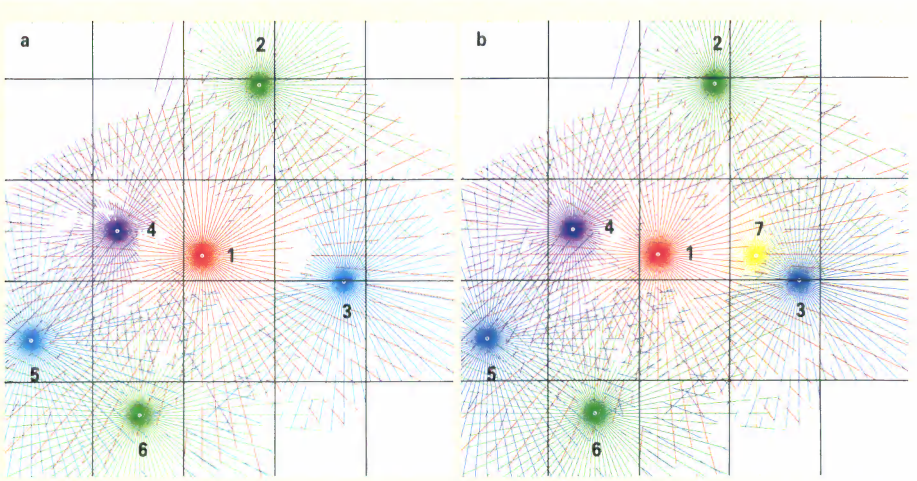

Fig. 4 Example of a service area
a Original configuration **b** With optimized parameters

morphographic profile calculated and plotted in this manner.

Calculation of received field strength

Four basic factors affect the propagation of radio signals:

- Free-space attenuation; this increases with the distance from the transmitter.
- Shadowing – and consequently attenuation – due to *topographic* obstructions, such as hills, mountains, gorges. The height and geographical location of such obstructions can be obtained from the topographic database.
- Shadowing due to *morphographic* obstructions, such as buildings and trees. The size and shape of these obstructions are not held in the database; their attenuating effect at the receiving location (mobile station) can only be determined statistically with the aid of the morphographic database.
- Scattering and reflections caused by obstructions in the immediate vicinity of the receiving location. The sometimes numerous wave components and their different, fluctuating phase relation to each other may cause severe fluctuations in the received field strength [1 to 3]. These fluctuations are not individually predictable and can only be determined statistically.

The electric field strength at the receiving location depends on the form and surface characteristics of the terrain between the transmitter and the receiver. Based on measurements performed by Siemens and by other workers worldwide [1, 4, 5], a method has been devised for calculating approximately the field strength at any point in the terrain. In accordance with [1], a distinction is made between quasi-plane and non-quasi-plane terrain. Quasi-plane is used to describe a gently undulating terrain whose elevations do not interrupt the line-of-sight between transmitter and receiver. In non-quasi-plane terrain, on the other hand, this path is obstructed by hills or mountains and, thus, no clear line-of-sight can be guaranteed between the relatively low vehicle antenna and the base station.

Experimentally derived statistical correction factors in the form of curves are given in [1] for the various categories of terrain, such as cities, suburbs, small towns, open country, forest and water. These factors take into account the difference between the mean field strength or attenuation in towns or suburbs, in quasi-plane or non-quasi-plane terrain, and for propagation over land or water.

Propagation model

The classic propagation model for the interpretation of empirically derived propagation data was produced by Okumura [1], who performed numerous field strength measurements in urban Tokyo and the surrounding Kwanto Plain. The frequency range employed extended from 150 MHz to 2 GHz, the effective height of the transmitting antennas lay between 30 and 1000 m and the transmission path was between 1 and 100 km. The height of the mobile receiving antenna was varied between 1 and 10 m.

Deygout [6], on the other hand, has given a theoretical model which accounts for the attenuation due to several obstructions, such as a series of mountain peaks, in terms of the knife-edge diffraction of electromagnetic waves (**Fig. 3**) and which exhibits close correspondence with results obtained in practice, provided there are no obstructions in the immediate vicinity of the radio stations. Causebrook [8] has proposed a modification to this, by means of which a systematic error in the calculation specified in [6] can be reduced.

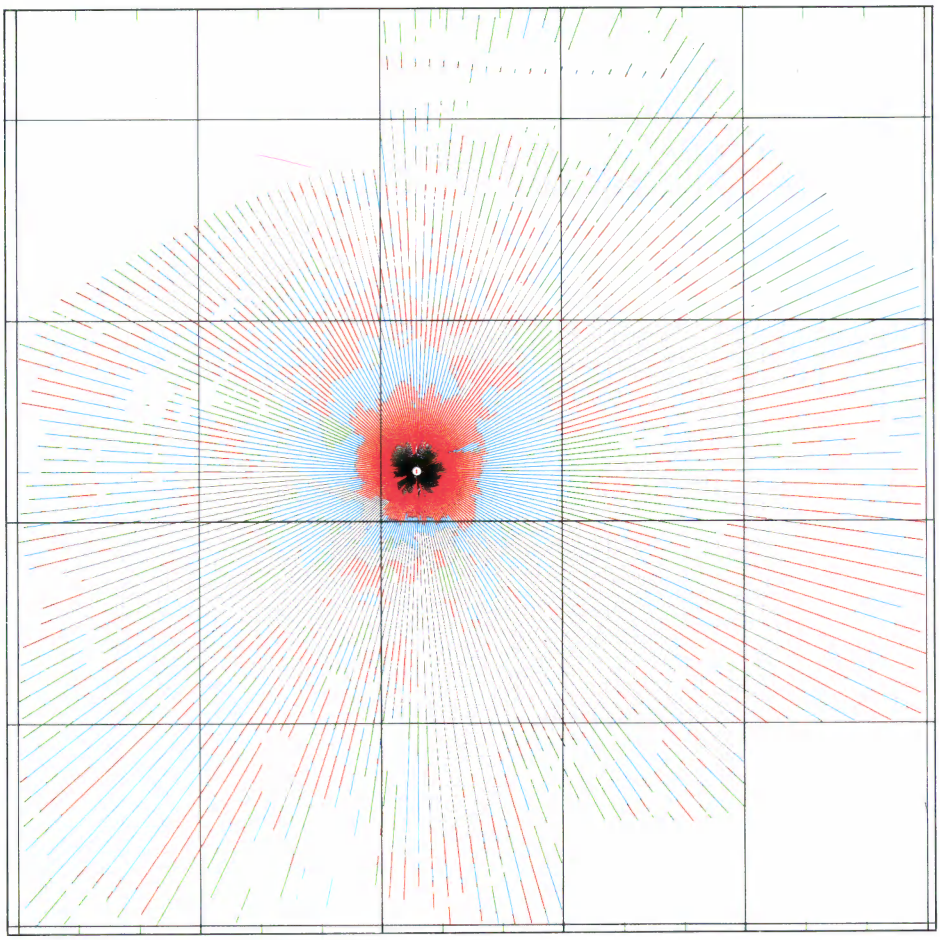

Fig. 5 Example of field strength distribution in 10 dB steps

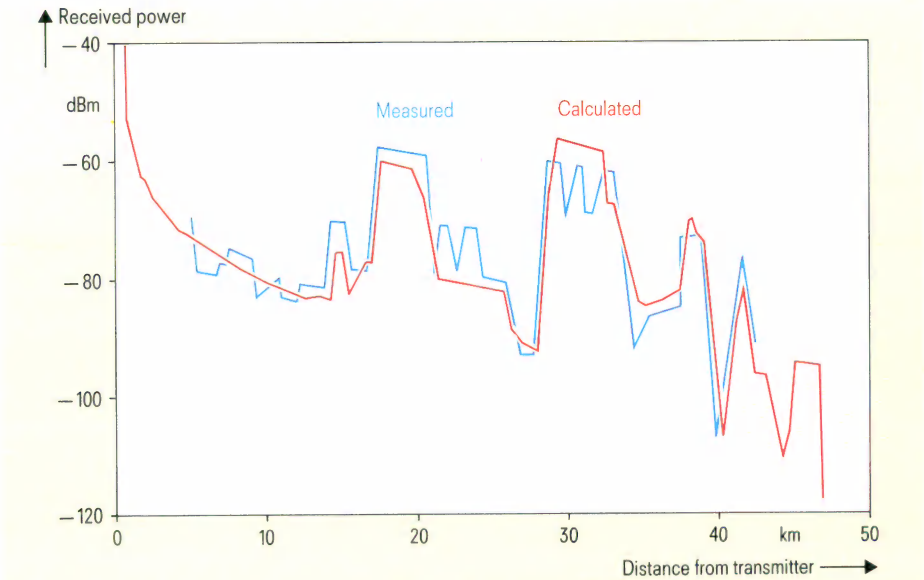

Fig. 6 Comparison of predicted and measured received power levels

In accordance with [7], the field strength calculation is here based on a modified model which combines Okumura's empirical process, Deygout's theoretical model and Causebrook's modification. According to this model, the median of the field strength level F_{mod} at the location of the mobile receiver is derived from the relationship:

$$F_{mod} = F_f + H_t + H_r - A_m + A_k - A_b - A_s + A_w.$$

Where:

$F_f = F_f(R, f, P, G)$ = field strength level for free-space propagation.

In quasi-plane terrain, the following correction functions are taken into account in accordance with Okumura's model:

$H_t = H_t(h_t, R)$
= gain due to height of base station antenna;

$H_r = H_r(h_r, R, M_o)$
= gain due to height of mobile station antenna;

$A_m = A_m(f, R)$
= attenuation in urban area;

$A_k = A_k(f, M_o)$
= empirical correction function for surface characteristics in the vicinity of the mobile station (per [1] and [7]).

For terrain which is not quasi-plane, the relationship must be extended by additional correction functions:

$A_b = A_b(f, R, h_t, h_r)$
= attenuation due to diffraction (per [6] and [8]);

$A_s = A_s(f, R)$
= influence of an extensive mountain slope (per [1]7 and [7]);

$A_w = A_w(f, M_o)$
= influence of a wooded slope (per [7]).

The parameters of these functions are:

f = Radio frequency;
G = Antenna gain (per antenna radiation pattern);
h_r = Height of mobile station antenna above ground;
h_t = Height of base station antenna (per [7])
M_o = Code number identifying the morphography of the area in question;
P = Transmitted power;
R = Base-to-mobile distance.

This model is applicable to radio paths of between 1 and 100 km and to effective antenna heights between 10 and 1000 m for the base station, and between 1 and 10 m for the mobile station.

The first step is to determine whether there is a body of water between the transmitter and receiver. If so, the attenuation is reduced by the ratio of the path over water to the path over land.

The calculation for terrain which is not quasi-plane is performed as outlined below.

First, a correction function is determined for the mountain slope in accordance with [1] and [7], if the terrain is inclined (i.e. rises or falls) at a distance of between 3 and 10 km from the mobile station. A check is then made to determine whether the line-of-sight between transmitter and receiver is interrupted by obstructions and whether, according to the definition in [4], such obstructions are too close to the base or mobile station.

If the line-of-sight is obstructed, the diffraction attenuation is calculated per [6] and [8]. To this end the main obstruction which causes the greatest attenuation by shadowing the first Fresnel zone is identified. In **Fig. 3** this is the mountain in the center, whose diffraction attenuation is calculated first. Independently of this, the diffraction attenuations are then calculated for the minor obstructions (mountains) which stand in the line-of-sight between the base station and the main obstruction as well as between the main obstruction and the mobile station. Finally, the sum of all individually calculated attenuations represents the total value of the diffraction attenuation between the transmitter and receiver. When corrected in accordance with [8], this value provides the final result.

Comparison of predicted and measured values

Using the procedure described above, the topographic and morphographic data of a large urban district and its surrounding area totaling 13,000 km^2 were extracted from 1:50,000 scale maps and stored. They formed a basis for the calculation of the radio coverage (field strength). **Fig. 4a** shows the field strength coverage in 5° steps around each base station for the urban area under investigation. The end of the individual rays or breaks in the lines signify "inadequate field strength"; i.e. the mean value of received power at the location in question is less than −95 dBm.

The areas of adequate field strength can be easily recognized in the diagram, but so too can the *pockets* in which the radio coverage is not guaranteed. In the example given, large *pockets* can be detected between transmitters 1 and 3 and near transmitter 4. In order to improve the radio coverage in these areas, a further set of calculations was performed. In view of the local conditions between transmitters 1 and 3, an additional base station (transmitter 7) was employed and the height of the antenna for transmitter 4 was increased. **Fig. 4b** shows the field strength coverage calculated with the modified input parameters. It provides adequate radio coverage.

The effect of transmitted power on the field strength distribution and on frequency reuse, for example, can be investigated if the field strength of individual transmitters is likewise plotted graphically by the computer in the form of ray diagrams. **Fig. 5** shows such a printout, in which areas of the same field strength are color-coded in steps of 10 dBm.

It was possible to verify the predicted field strength distribution to a sufficient degree of accuracy for practical purposes using a test vehicle. The measured sections with a total length of around 4000 km were selected such that all parts of the service area which the calculation predicted as being critical or possibly with inadequate field strength were measured. The differences between the calculated and measured received power levels exhibit a normal distribution with a spread of about 5 dB.

The calculated and measured values for a specific path profile are compared in **Fig. 6**. The close correspondence between the predicted and measured values is immediately evident from this comparison.

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Gottfried Schreiner and Detlev Stumme

Project Planning and Construction of Earth Stations

Siemens has been involved in the planning, engineering and equipping of earth stations since the inception of satellite communication. Turnkey systems for commercial communication traffic have been constructed in many countries and are distinguished by their high reliability. Special precautions ensure that communication is undisturbed even under the most difficult climatic conditions. The advantage of direct access to a worldwide communication network is being exploited not only by the industrial countries but also by countries not located on the main communication arteries. The increasing demand for communications is therefore leading to the use of ever more sophisticated satellites, the expansion of existing earth stations and the construction of new ones. This article describes the planning and construction of an Intelsat Standard A earth station.

Earth station construction and operation is the responsibility primarily of the PTT administrations of Intelsat member countries which are bound by the specifications they have jointly produced. In addition, the future operator specifies other characteristics in his system specification which forms part of the document issued to the industry as a public invitation for bids.

The Marketing and Sales department, operating through Siemens' local companies and agencies worldwide, maintains contact with the PTTs of all Intelsat member countries in order to ensure that any projects for construction or expanding earth stations are included in Siemens' own planning process as early as possible. If, after the bidding conditions have been examined from a technical and economic point of view, it is decided to compete for the contract, work is started immediately on preparing the bid.

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Project planning phases

At the outset of preparing a bid, Siemens forms a *project-oriented working group* in order to be sure of presenting the client with a technically and economically optimized proposal. The Sales and Marketing, Development, Production, Project Planning and Field Services departments pool their planning resources so that the results of their proposal in the bid document will give the client a clear idea of the technical characteristics, cost and timescale of the construction project. The main areas to be considered in the construction of an earth station are listed below:

- site location,
- feeder services,
- civil engineering and construction work,
- steelwork,
- installation of communication equipment and facilities,
- power supply,
- service supervision,
- personnel deployment.

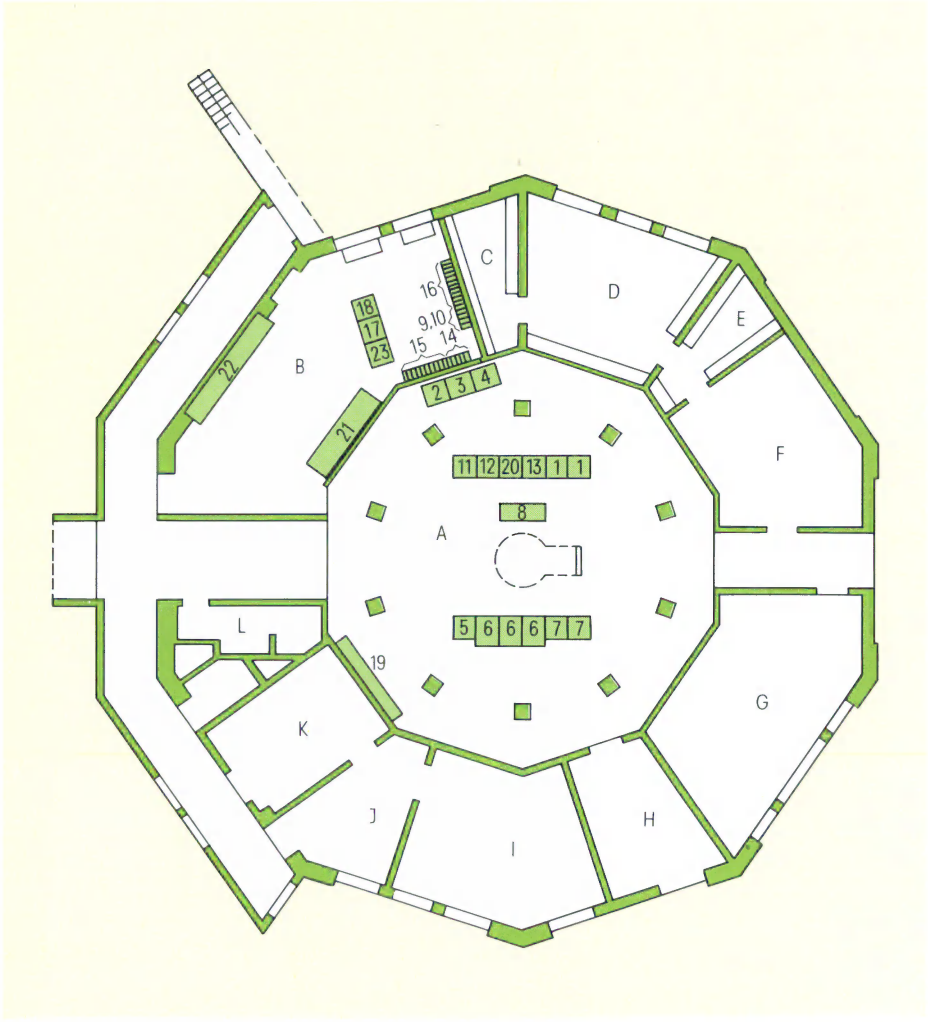
Site selection

When selecting the site for the earth station, it is necessary to consider not only the existing infrastructure and topographical factors, but also a number of other factors [1]. Some examples of these are given below:

- The site should be free of radio frequency interference from transmitter installations, radar stations and radio relay routes within a radius of 10 km.
- There must be no air traffic in the immediate path of the main beam (an aircraft can interrupt a radio link to the satellite for about 150 ms).
- It is advisable for the site to be at least 3 to 5 km away from expressways and railroads in order to avoid radio-frequency interference.
- The terrain should be as flat as possible and the subsoil sufficiently stable to obviate the need for complex foundations.
- Natural shielding around the site should be provided in the range of 3° to 5° elevation angle.
- Access facilities must be provided in advance for heavy transport vehicles carrying oversized loads.
- The primary energy supply is normally obtained from an electric power transmission network.
- The earth station may comprise several antenna systems and buildings depending on the volume of traffic. In order to avoid mutual interference the antennas should be kept 200 to 300 m apart. The site chosen must be of suitable size to allow for possible expansion.

Feeder services

The earth station can be linked to the terrestrial network via coaxial or fiber-optic cables or by radio relay. In the case of radio relay links, careful consideration must be given to frequency and site selection as well as antenna tower height to take account of possible interference in the 4-GHz and 6-GHz bands.



1	Engineer service channel equipment	19	Power distributor
2	Servo control rack	20	Supervisory rack
3	AZ power control	21	Control console
4	EL power control	22	Teleprinters
5	TX control rack	23	Test rack
6	High power amplifier		
7	Up-converter	A	Equipment room
8	Low-noise amplifier	B	Control room
9	Baseband distributor	C, E	Store room
10	Demodulators	D	Workshop (mechanical)
11	Down-converter	F	Workshop (electrical)
12	RX supply and control rack	G	Air-conditioning system
13	Signal distributor	H	Power distribution
14	Modulator	I	Station manager
15	Multiplex equipment	J	Secretary's office
16	SCPC equipment	K	Kitchen
17	TV monitor	L	Washroom, toilet
18	Test and recording equipment		

Fig. 1 Equipment and ancillary rooms in an Intelsat Standard A antenna (compact system)

The earth station interfaces with the feeder route at baseband (BB) frequency. Since the individual channel capacities for intercontinental links are often small, it is usual to combine telephone channels for several countries in one baseband. By using multiple-access carriers the number of transmit carriers in an earth station is low, yet the number of receive carriers is a multiple of the transmit carriers.

Civil engineering and construction work

In the "compact system" design (**Fig. 1**) the antenna substructure accommodates not only the drive control facilities but also the entire communication equipment and auxiliary facilities. Large systems, on the other hand, comprise several antenna buildings (housing, the drive system and parts of the transmit and receive systems), a main building for operation monitoring and control as well as buildings for power supply equipment and standby ac power plant. It may also be necessary to construct ancillary buildings for staff and administrative purposes. The technical buildings are interconnected by underground cable ducts.

From the results of a soil survey it is known what foundation work is required and the type of foundation to be employed. A suitable, national construction company is contracted to carry out the civil engineering and construction work. The antenna building fulfills a dual function in providing an operations area and support structure for the moving antenna. In the case of a *wheel-on-track antenna,* the antenna substructure is surmounted by the circular track (diameter about 18 m) which is required to transfer all the vertical forces (about 240 t) to the structure below. The azimuth bearing in the upper part of the cone ensures circular antenna movement and absorbs all horizontal forces (wind).

On a *turning head antenna* the vertical and horizontal forces are transferred via the central azimuth bearing system to the cone-shaped antenna building.

Accommodation of the communication equipment

The communication equipment and ancillary facilities of an earth station together with the antenna form the earth segment which establishes the connection between the terrestrial network and the space segment, i.e. the equipment accommodated in the satellite. All the equipment in this chain is subject to exacting requirements in order to provide high-quality transmission and high reliability.

Redundancy circuits increase reliability, i.e. one or more operating units are assigned an identical standby unit to which traffic is transferred automatically in the event of a fault. High-quality transmission is achieved, inter alia, by maintaining a high signal-to-noise ratio in the entire signal path. In order to minimize power losses, it is necessary, for instance, to position the low-noise preamplifiers of the receive system and the power amplifiers of the transmit system as close to the feed point of the

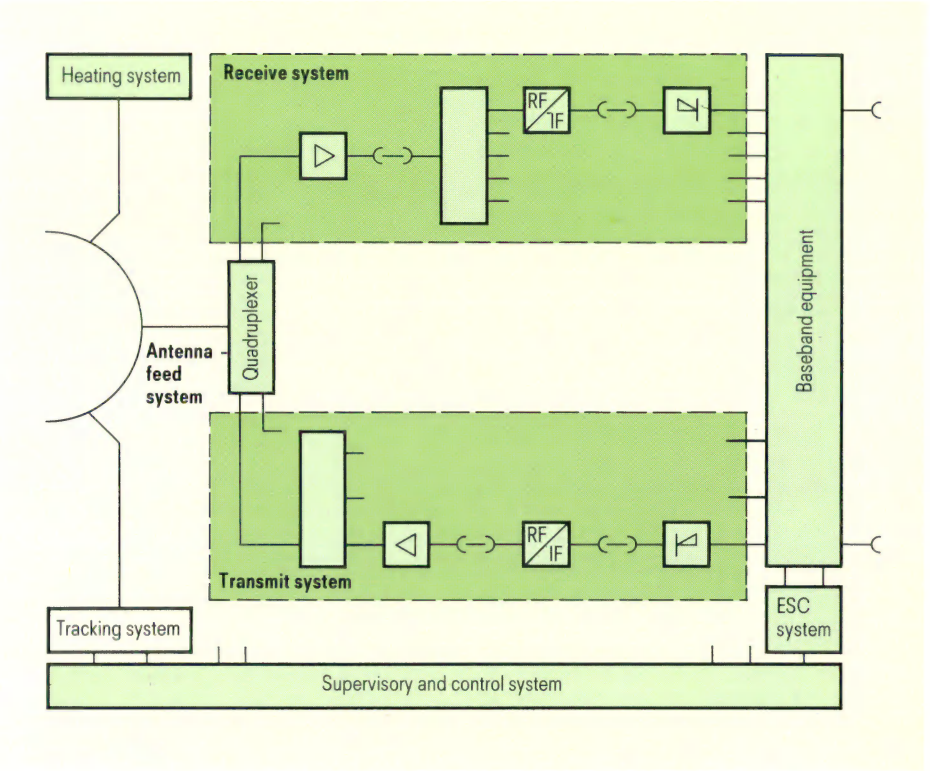
antenna as possible. However, since most earth station operators require all equipment to be stationary for ease of maintenance and access, the feed point is located in the axis of azimuth rotation to allow the communication signals to be transmitted via a rotary joint between the rotating antenna and the fixed substructure. As a result, the substructure required as a foundation for the rotating antenna is designed as a building which also conveniently provides accommodation for the equipment and facilities required for the antenna system.

In large systems some of the equipment is accommodated in the main building from which the communication signals are fed via cables at intermediate frequency (IF) or at radio frequency (RF) to the individual antenna buildings. In addition, the control facilities in such systems are designed to permit remote operation so that the antenna buildings can be operated as unattended stations.

The need to accommodate a large proportion, at least, of the communication equipment in the antenna building requires a well thought-out equipment layout plan in order to keep critical interconnections as short as possible, while maintaining adequate space between rack suites for operational purposes. One difficulty in achieving this is that the layout of equipment must be decided at a very early stage in the planning process while there is still an opportunity for influencing the design of the building, e.g. as regards

- the dimensions of the building as well as its horizontal and vertical subdivision,
- the openings for cables, waveguides and ventilation ducts,
- the clearance between columns or load-bearing walls,
- the size of door openings,
- the load-bearing capacity of the floor and ceiling.

The main facilities of an earth station are shown in the functional diagram in **Fig. 2**.



ESC Engineer service channel
RF Radio frequency
IF Intermediate frequency

Fig. 2 Functional diagram of an Intelsat earth station

Power supply

An important aspect of planning an earth station is the provision of an adequate and continuous source of power. A suitable system must be chosen from the available range, e.g.

- standby ac power plant,
- peak-load plant,
- continuously operating set,
- rapid-starting plant or
- hot-standby plant.

A suitable means of powering satellite earth stations has proved to be a combination of several types of systems as discussed in detail in [2]. The 3 × 380 V station supply derived from the power transmission network is backed up by a standby ac power plant (starting delay up to 10 s). This combination is followed by a dual, battery-fed inverter system which supplies the communication facilities, such as the transmit and receive systems, modems and multiplex equipment as well as the equipment on the feeder routes. Lighting, air conditioning, antenna drives and possibly reflector heating are fed from the standby ac power plant.

Actual execution of an earth station project

If the bid for the contract to construct an earth station has succeeded against international competition, the next step is put the prior planning into effect. For this purpose, a *project group* is formed with responsibility for coordinating technical departments and subcontractors, for scheduling and progressing as well as for controlling production, installation and commissioning. The project group comprises a project manager, the systems engineer, sales, marketing and commercial executives, the site manager and the person responsible for construction and commissioning.

A schedule is drawn up as a basis for further action, using modern, computer-aided methods, such as SINET (Siemens critical path analysis). The responsibility for meeting schedule commitments for

- provisions to be made by the client (site, on-site power, infrastructure, telephone),
- services by subcontractors,
- goods supplied by outside firms and
- in-house scheduling

rests with the project group.

The schedule is monitored and updated throughout the duration of the project. Any matters likely to affect the final completion date are discussed immediately with the client. In-house, the scheduling groups initiate production of

the required equipment, and the necessary contracts are placed with subcontractors and outside firms.

The station design planning group prepares all the necessary station-related design documents and initiates the provision of requisite cable types and quantities. As enquiries proceed, this group prepares other documents, such as cable routing diagrams, jumpering diagrams and distributor wiring diagrams, as well as establishing interfaces. At the same time, the items specific to the particular station, such as the RF switching system, combining network and receive waveguide system, are designed and put into production.

All the items to be supplied find their way initially to the order make-up department. Large containers have proved to be a convenient way of shipping the numerous components, such as cables and lines, installation consumables, racks and equipment. These containers can then be used on site for storage purposes.

When constructing an earth station abroad it is important to clarify the relevant customs regulations with the client and the local Siemens company in advance. It is also necessary to obtain shipping and installation insurance. For the construction phase, a site office is established – together with the subcontractors – from which the site manager can operate.

The normal procedure is to arrange for the majority of work on the site to be performed by local personnel.

When installation and commissioning are complete, the client's operating staff is trained in operating the system according to the O & M concept (operation and maintenance). The concluding tests for Intelsat approval are performed jointly with the client.

Today Siemens is capable of completing a turnkey earth station, from award of the contract through handover to the client, in less than 18 months.

Steel structure supporting the reflector

The most conspicuous aspect of any large directional antenna is the steel structure supporting the parabolic main reflector and the other parts of the feed system.

Siemens' Intelsat Standard A antennas have a main reflector 32 m in diameter with a wide range of movement in both azimuth and elevation. The factors determining the quality of the electrical characteristics of the antenna include the profile accuracy of the reflector surface and the precision of the feed system geometry, i.e the distances and angles between feed horn, deflecting mirrors, subreflector and main reflector. For this reason, any distortion of the support structure due to wind loading or gravitational effects (elevation movement, icing) must not exceed the specified tolerances. Accordingly, the box-section and tubular members forming the spatial framework of the main reflector structure and the steerable azimuth mount are arranged and dimensioned to exceed the specified strength and thereby achieve the required stiffness.

Planning, calculation, design and production of the machinery and steelwork for the antenna are subcontracted to an experienced steel fabricator. The type of antenna, its mechanical characteristics and all interfaces to the associated subsystems are defined precisely in a specification agreed between the main contractor, as system leader, and the subcontractor. This document includes the following main features:

- *Antenna design*
The decision regarding antenna design (either the wheel-on-track or turning head principle) has a significant impact on the design of the antenna building.
- *Feed system principle*
(e.g. central feed or beam waveguide feed system with deflecting mirrors).
- *Setting accuracy* of all important dimensions and their tolerances under the effects of gravity, wind and temperature.
- *Drives, braking and locking devices*
Since the antenna and its mechanical assemblies form part of the tracking control system, it is necessary to maintain specified dynamic characteristics.

Although the subcontracting steel fabricator assumes the responsibility for designing, manufacturing, installing and adjusting the antenna structure, the main contractor must perform a number of coordinating, supervisory functions. These include specifying and monitoring important scheduling dates as well as assuring quality by participating in factory and site acceptance tests. The antenna installation sequence is described briefly below.

In shipping the components and assemblies to the site it must be remembered that some of these items are very large and heavy, placing special demands on the transport facilities and access routes. The decision as to whether the items are to be moved by ship, aircraft and/or truck has an impact during the design stage [3].

The main reflector is completely assembled on specially constructed auxiliary foundations next to the antenna building (**Fig. 3**). Its contour, established during the electronic development stage, is formed by a total of 228 individual panels which are held on the reflector structure by adjustable bolts. If the climatic conditions require it, the panels can be fitted with heating elements to keep the reflector surface clear of snow and ice.

As soon as the basic structure of the antenna building is complete, the work of installing the azimuth bearing and the track (e.g. for a wheel-on-track antenna) can begin. The next step is to erect the azimuth mount, the top of which houses two elevation bearings. With a crane of suitable capacity the main reflector, which weighs some 120 t, is raised in one piece and placed on the azimuth mount (**Fig. 4**). Once the necessary alignment and securing operations have been completed and the steering gears, including the motors, have been fitted, the antenna can be rotated and tilted. At this stage, power control of the antenna tracking system is available to the extent that electrically controlled antenna movements are possible.

The installation work is followed by extensive testing and adjustment, the most important aspect of which is to set the main reflector contour. Optical measuring methods and a computer-aided process are employed in several passes to locate each of 912 test points. The individual panels are so adjusted that deviations from the ideal profile, when the antenna is operational, are less than 0.5 mm (rms). These measurements are normally performed at night (with no wind if possible) in order to eliminate the effects of temperature due to variations in insolation (position of the sun, clouds) (**Fig. 5**). Other opera-

Fig. 3 The main reflector is assembled on the ground near the antenna building

Fig. 4 Placing the nearly 120 t main reflector on the azimuth mount

tions for which the steel fabricator is responsible are the installation and alignment of the large components for the feed system, such as circular waveguides, feed horn, deflecting mirrors and subreflector. Precision optical measuring equipment is used first in order to establish the correct location of these components.

Installing the antenna tracking system

After the main reflector has been placed on the azimuth mount and the steering gears have been installed, work begins on installing the drive motors with tachogenerators, the limit switches and resolvers together with the associated cables. At the same time, the power racks and the control rack for antenna tracking are installed and connected. Those cables leading from fixed racks to equipment which follows antenna azimuth movements are routed via the cable turning system, i.e. they are secured to a moving multiple-coil steel helix in such a way as to protect them against damage (**Fig. 6**). Contactless limit switches restrict the range of antenna movement (0 to 90° elevation, about 315° azimuth); the dead region in azimuth is usually set symmetrically to north (for sites on the northern hemisphere).

Since there is no tracking signal available at this stage, the first part of the tracking system to be commissioned is that which allows manual control of the antenna to any desired position within the specified limits for further installation and adjustment operations.

Installation and adjustment of the feed system

Reference has already been made to adjusting the main reflector contour and to installing and setting the feed horn, deflecting mirrors and subreflector. On an antenna with a beam waveguide feed system and two deflecting mirrors, the feed horn is suspended in the structure so that it is inclined at an angle of 11° to the azimuth axis. The beam from the horn is incident on the first deflecting mirror located in the elevation axis and is reflected from there onto the second deflecting mirror which is located at the intersection of the elevation and main reflector axes. From this second mirror the beam is deflected through the apex

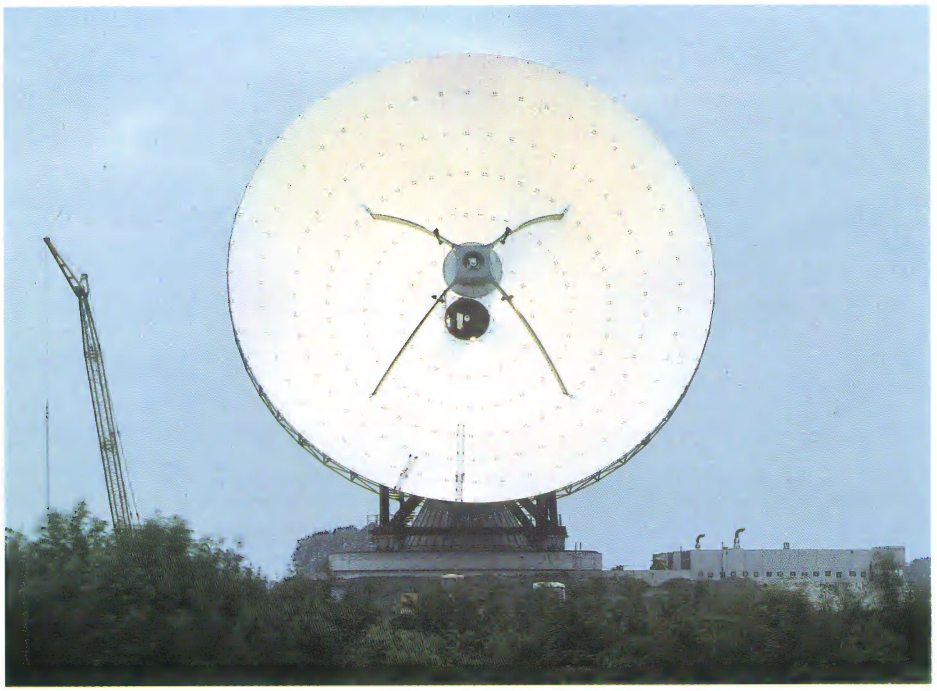


Fig. 5 Measuring the contour accuracy of the main reflector at 912 test points is performed at night to avoid unwanted temperature influences

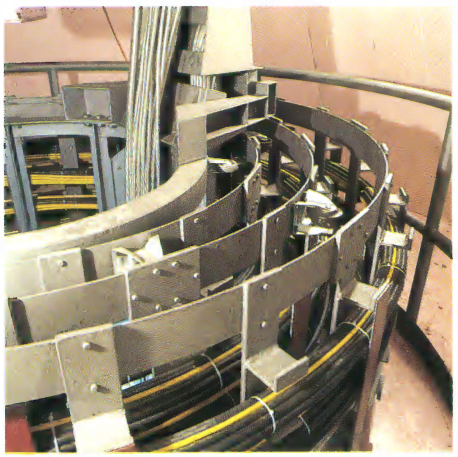


Fig. 6 Cable turning system on the upper floor of the antenna building protects cables from being damaged by antenna movement

opening and onto the subreflector [4, 5]. The contour of the subreflector is designed to ensure that the main reflector is optimally illuminated according to the specifications.

In addition, the feed flange of the corrugated horn is connected to a low-loss circular waveguide about 6.40 m long. This waveguide establishes, via a mode coupler and waveguide bend, the connection to the azimuth rotary joint which is concentric with the azimuth axis at about the level of the equipment room ceiling. The supports for the circular waveguides and rotary joint are adjusted to minimize the mechanical forces acting on the electrical components. It is particularly important to ensure that, as the antenna turns, no stresses occur in the flange joints to the stationary waveguides as a result of eccentric rotation.

The feed system also includes the transmit/receive polarization diplexer, the so-called quadruplexer. This is flange-coupled to the stationary section of the azimuth rotary joint and links the feed system of the antenna to the receive and transmit equipment for two orthogonal polarizations in each case. The waveguide run, including the corrugated horn, is checked electrically both in the factory and when installed on site.

When the antenna has been fully installed and adjusted and the low-noise preamplifiers and at least one power amplifier have been put into operation, it is then possible to pretest all the parameters of the antenna system via satellite. In the course of these tests, the optimum position of the subreflector in the Z axis (direction of beam to the deflecting mirror) is found and finally fixed.

Installation of the transmit, receive and auxiliary equipment

Before all the remaining communication equipment can be installed, the equipment room must first be fitted out to include air-conditioning and ventilation ducts, false flooring (computer flooring) and interior wiring. The only operation which can be carried out earlier is that of leading in the intersite cables to the main building. Similar requirements also apply to the main building.

It is convenient to begin in the antenna building by installing the waveguide switching and combining network in a tubular framework secured to the ceiling (**Fig. 7**). Another structure suspended from the ceiling is that supporting the low-noise preamplifiers which must be located as closely as possible to the receive signal outputs of the quadruplexer.

Finally, the racks for the power amplifiers, the up-converters and down-converters as well as the control and supervisory equipment are installed in accordance with the equipment layout plan, taking account of the requirements of the different mounting styles (19 inch, 600 mm or style 7R narrow racks). The rack suites are positioned far enough from each other with a gap between the end of the suite and the wall to ensure that there is always an unobstructed escape route in the event of fire or high-voltage accident.

If there is a main building and IF transmission is employed, the modulators and demodulators as well as the remote indicating and control equipment are installed in the rooms provided, taking the same considerations into account. This building would also house the baseband and multiplex equipment providing the connection to the feeder services (e.g. radio relay route).

The electrical connections between the individual equipment units are established using a wide variety of techniques. While connections at RF employ mostly waveguides and semi-rigid cables, at IF (70/140 MHz) they are always coaxial cables. At baseband, coaxial cables predominate with some use of balanced-pair lines. Control and supervisory functions employ multiconductor signal cable, while power connections are established using the lines specified by VDE, IEC or equivalent national regulations.

The cabling can be conveniently routed under the false floor, but measures are

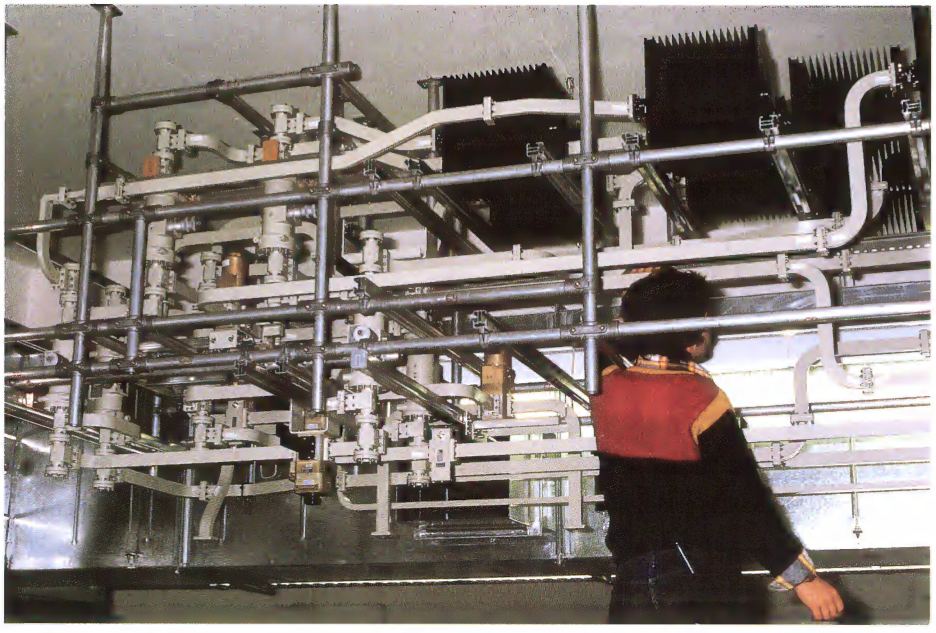


Fig. 7 Installing the waveguide switching and combining network on the ceiling of the equipment room

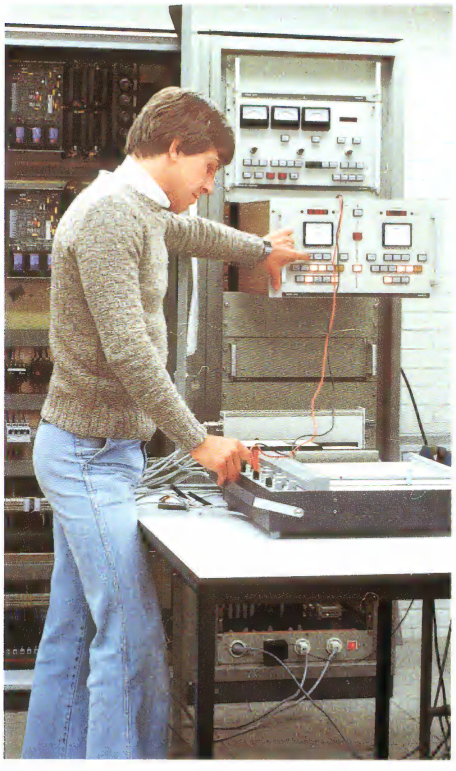


Fig. 8 After installation the antenna tracking system is tested and put into operation before final acceptance testing with the client

necessary to minimize mutual interference (e.g. maintaining certain distances, avoiding crosses, using cable bridges to transpose cables, fitting shields, etc.).

In order to compensate for structural tolerances and slight distance variations, the power amplifiers mounted on the floor are connected to the ceiling-mounted waveguide switching system via flexible waveguides. The quadruplexer, flange-coupled to the rotary joint, has a similar flexible connection to the waveguides of the receive and transmit systems. In earth stations equipped for TDMA operation (time-division multiple access) it is important to ensure that the signals always travel equal path lengths, whether in the operating or standby path, thus eliminating inadmissible time delay differences in the event of redundancy switching.

Once the installation work is complete, the various units are switched on and lined up (**Fig. 8**). The subsystems are then interconnected, tested and prepared for acceptance testing. With the client's acceptance officers in attendance, the acceptance tests are performed and documented on prepared forms. If all measurements are to specification, the client declares the earth station accepted and applies to Intelsat for permission to participate in international communication traffic.

Supervision of earth station operation

In order to meet the exacting requirements on the service reliability of an earth station, all the main systems are provided with redundancy circuits which automatically switch to a standby unit if the operating unit develops a fault. In addition, supervisory systems signal every detected fault to a predetermined main station where the messages are received by operating personnel. A fault in a unit produces various levels of response, for example,

- in the *rack and suite fault signaling:* the fault message produces a rack alarm which in turn initiates, via an indication converter, a suite alarm in the rack at the head of the suite;
- in the *system fault signaling:* the fault message produces a system alarm initiating a predetermined changeover and a suitable display;
- in *fault recording equipment:* the fault message is recorded with details of the time and printed out;
- in a *remote supervision facility:* the fault message is transmitted to a distant location where it is displayed.

Since these different systems must not be interlinked, several floating contacts for alarm signaling are required in each rack and are jumpered via extensive signal distributors to the individual signal detectors. If a unit does not provide sufficient alarm contacts, the existing ones are multipled in a relay unit. The relays employed for alarm signaling operate on the closed-circuit principle.

The alarm signals are transmitted from the antenna to the main building using either parallel or serial techniques. Serial transmission is assuming greater importance due to the increasing use of computer-aided monitoring systems to evaluate the message. In addition, these modern systems can also process and display numerous status messages, switching states, etc. so that, for instance, a color monitor can be used to display the current status diagram of an earth station at various resolution levels [6].

While the remote message and control equipment undergoes acceptance testing with the associated operating units, the alarm signal functions are checked in the course of system testing. Since it is not always easy to provoke a selective alarm signal, this test needs to be suitably well prepared. It is also necessary for all the individual units to be set correctly and operating properly in order to ensure that the test is not disrupted by unwanted alarm messages.

Prospects

The increasing use of satellite communication is creating more opportunities for earth station construction. This is due to such factors as the use of higher transmission frequencies, time-division multiple access, master stations for videotelephony and high-speed data transmission, etc.

Siemens is taking a leading role in these developments and provides modern earth stations for all planned national and international services. The contracts are handled on an extremely flexible basis to allow clients' special requirements to be taken into account. This applies not only to the construction of new antenna systems but also to the expansion and modernization of existing stations. In addition to expert planning advice and the supply and installation of reliable equipment, another most important factor in this sector of the market is effective after-sale service.

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Planning and Commissioning Mobile Radio Systems

The new digitally-controlled C450 cellular mobile radio system is technologically one of the most advanced telecommunication transmission systems.

Its flexible system structure allows the configuration not only of small-scale, self-contained isolated networks, but also of nationwide or international mobile radio networks as an integral part of a public telephone network. In addition, all system components, such as base stations, mobile switching centers and user equipment (mobile stations), can be adapted to growth in traffic in economical stages appropriate to the size of the network.

In systems such as these, the transmission and call-processing equipment must be fully compatible. This calls for extensive knowledge in the fields of radio and wireline transmission on the one hand, and digital switching technology on the other.

The C450 mobile radio system, with its special operating features, has been designed and developed over the last few years as a result of close collaboration between the "Transmission Systems" and "Public Switching Systems" divisions in the Telecommunication Networks and Security Systems Group of Siemens. The planning and commissioning of such systems by a single organization results in extensive tasks of a preparatory and project-related nature as well as those specific to handover. For the C450 system, full use was made of Siemens' worldwide experience in the installation of complex communication systems.

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General planning criteria

The C450 mobile radio system offers the user a wealth of new opportunities for shaping the structure of the radio network.

The planning of a mobile radio network must take into account all criteria, which can be derived from the traffic requirements as well as from the radio propagation conditions. These may differ widely from cell to cell and the proposed solution must therefore be tailored to the individual case. Radio propagation criteria in mobile radio systems differ fundamentally from those of the familiar radio relay routes, since the links between a base station and a mobile station are mainly established over propagation paths beset by the problems of obstructions and reflection.

As a result of the low elevation of the mobile station antennas, which in most cases are dwarfed by the surrounding obstructions, and the continuously changing location of the vehicle, the radio path characteristics are unpredictable and highly individual. Precisely detailed planning of the radio network is therefore an essential requirement for a wide-area mobile radio system which is economical to operate.

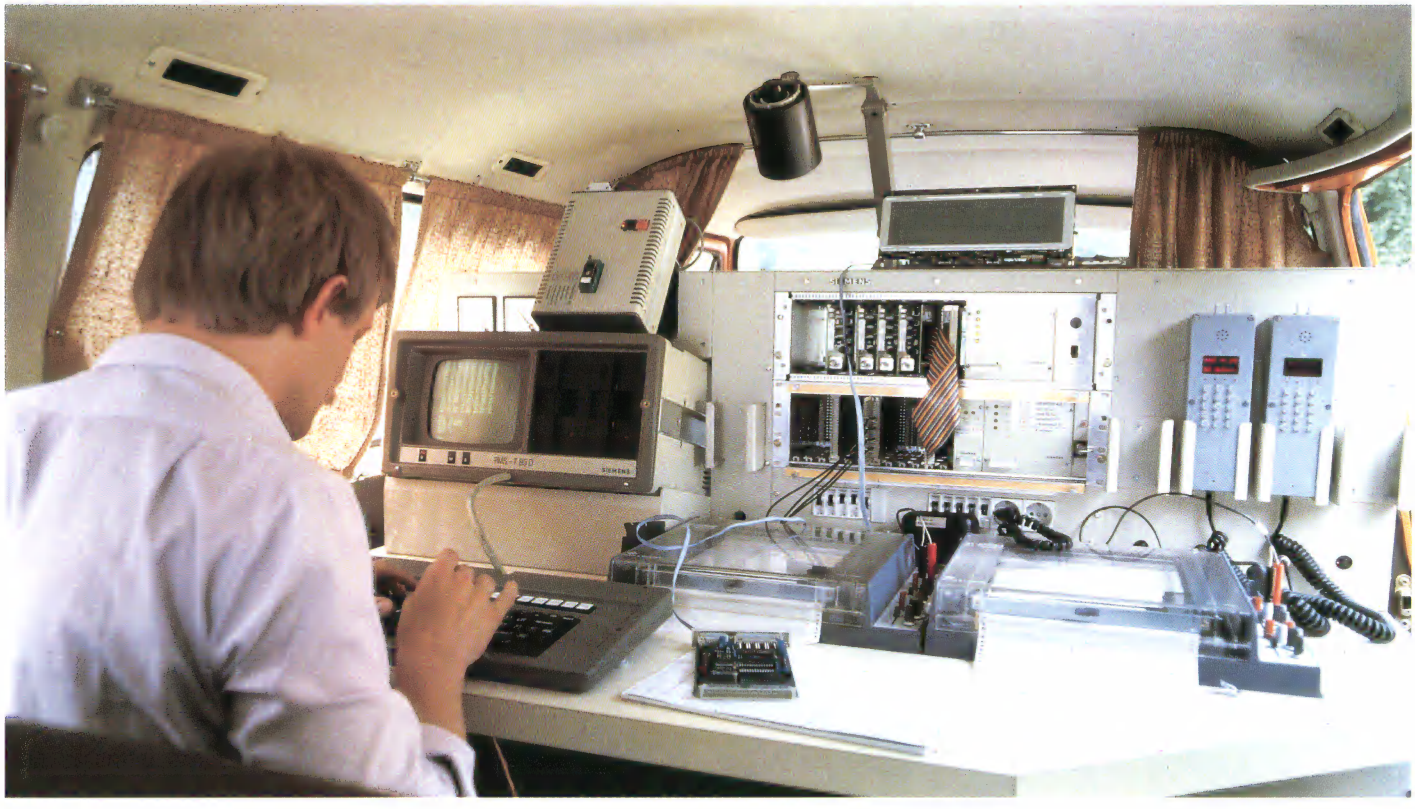


Fig. 1 Inside a test vehicle

The essential criteria, which are measured and processed by the system and which can affect a cell by changing parameters in the base station file, are the values of

- field strength of the received signal,
- jitter of the digital signals and
- delay between the base and mobile stations.

These values incorporate the influence of the terrain and they therefore constitute an important factor in the planning of such a network.

In practice, it is often impossible to measure the field strengths for planned radio networks, due to the lack of sites for base stations or the inaccessibility of some areas. Since field investigations of the effects of differing power levels, antenna heights and antenna radiation patterns on the received field strength in a service area and on the reuse of channel frequencies would be very costly, a theoretical, computer-aided calculation of the radio coverage of the service area is made with data from topographical maps.

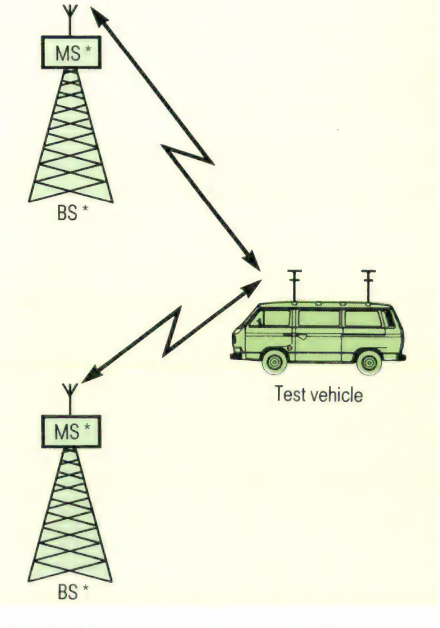
By repeatedly adjusting the location of the base station, the transmitted power, and the antenna height and radiation pattern, optimum radio coverage can be determined with the aid of a special computing procedure.

Radio propagation measurement

A test vehicle (**Fig. 1**), developed specifically for the C450 mobile radio system, is used for checking the computed results and also to record and register all relevant radio data from up to seven base stations. This vehicle is also used for performing the system function test.

The equipment in the vehicle is so arranged that system maintenance functions can also be performed during operation simply by changing the test software.

For radio propagation measurements in the project planning phase, base stations can be simulated by installing up to seven mobile stations with omnidirectional antennas on existing radio towers, or with an antenna on a mobile telescopic mast at alternative sites (**Fig. 2**). These equipments are designed for operation from commercial power or battery. The mobile station installed in the test vehicle is suitably modified for the intended measuring functions.



* Simulated base stations (BS), equipped with up to seven standard mobile stations (MS) and a 5 dB omnidirectional antenna

Fig. 2 Arrangement for measuring radio propagation characteristics

Radio data are determined continuously and automatically by the mobile stations. The measured data are exchanged between the base stations and the test vehicle via the permanent radio data

link. In order to check the voice signal quality and to establish contact with the test vehicle, calls can be set up between a base station and the vehicle in the duplex operating mode.

A microprocessor in the test vehicle performs the task of editing the measured data and storing them on a data medium (floppy disk). At the same time, these data are displayed on a video terminal and a hard copy is produced by a printer. An additional means of output is available in the form of a plotter, on which any two variables, e.g. field strength and jitter, can be recorded in analog form.

By using C450 mobile stations at the planned base station sites and in the test vehicle, the measuring system simulates the essential parameters of the equipment functions in an actual network. As a consequence, the results of the measurements can be applied directly to the planned network. The route traveled by the test vehicle is influenced by the size of the service area and must be selected with particular care and in accordance with the following criteria:

- Results of the theoretical field strength calculation,
- Main highways and
- Cell boundaries.

Checking the results from critical areas against the preceding theoretical field-strength calculation provides information on the accuracy and reliability of the predictions. In this way, a conclusion can be drawn on the extent of the agreement between calculated and measured values. While the theoretical location of cell boundaries is determined by calculation of the field strength, bounderies established by means of the measuring process in the test vehicle, just as in the practical network, are determined by the phase jitter limit.

In calculating the cell boundaries on the basis of field strength, the factors influencing the radio path are included with appropriate safety margins. This does not, however, take into account the interference caused by reflection, the primary effect of which is increased phase jitter. This interference arises from the reception of signals having approximately the same field strength, but which take different paths and are therefore of different phase.

Thus at the receiving locations, aggregate signals result whose RF levels, while having mean values, have phase angles which depend on the location of the mobile station.

If the mobile station moves, a continual shifting of the received signal phase occurs, which directly affects the transmission quality in the form of phase jitter. As the speed of the mobile station increases, this jitter value rises and the quality of transmission deteriorates. Another variable not included in the theoretical field strength calculation is the measurement of the distance between base and mobile stations in the vicinity of cell boundaries.

These measured data can be used to determine cell boundaries for the externally controlled handoff from one cell to the next. Distance measurement is based on measurement of the relevant received signal phase. As the phase of a phase-locked transmit signal changes only as a function of the radio path, the distance from the transmitter can be determined by the receiver evaluating the signal.

The base station transmitter – or the transmitter of the mobile station in the case of the test vehicle – is phase-locked to provide a reference. The signal arrives at the mobile station receiver after a delay corresponding to the length of the radio path. The mobile station located at the base station then corrects its own time reference and thus the phase of the associated transmit signal, which likewise experiences a delay dependent on the radio path. The difference in time is thus proportional to the base-to-mobile distance.

The test routes selected on the basis of the theoretical calculations yield all the required data and information concerning the siting of the base station and the creation of the station-specific file, as well as possible network structure, radio coverage and antenna radiation pattern.

Project planning

At the start of project planning, individual responsibility is assigned for the mobile switching center, the radio network and the customer-furnished element. The latter includes, for example, the provision of the infrastructure, such as buildings, towers, access roads, electrical power, antenna systems and data and voice lines. Siemens is able to contract either for parts of, or for the entire project and to ensure delivery on schedule.

The most important document for the planning and construction of a wide-area mobile radio network is a questionnaire, from which all points relevant to the construction can be cleared during a field inspection.

The most important of these points are:

- Establishing a timetable for the construction and commissioning of the base stations, coordinated with the construction and delivery of the antenna system and of the mobile switching center;
- Determining the type of antenna, which depends on the required radiation pattern and the number of radio channels;
- Investigating existing antenna-bearing structures (steel lattice or concrete towers);
- Examining the construction drawings for existing towers;
- Assigning space for the base station equipment with allowance for the foreseeable expansion of voice channels;
- Considering the use of existing openings in walls and ceilings for the cabling and antenna feeders;
- Ensuring uninterrupted power supply for a base station incorporating redundancy (typical value: about 2 kW for five voice channels and about 6 kW for 20 voice channels).
- Planning for a base station in a shelter-type structure where the infrastructure is inadequate;
- Laying of voice and data cables and connecting them to the mobile switching center,
- Producing installation and layout drawings;
- Providing installation materials;
- Planning the personnel requirements for network construction.

Computer-aided project monitoring and the coordination of the customer-furnished element play a significant part in the construction of the system on schedule. The preparatory work for the commissioning of the network takes place in parallel with these activities.

Measurement records and tolerances must be agreed upon, so that commissioning operations can begin as soon as installation has been completed.

Commissioning

Introducting computer-controlled transmission systems increases the flexibility of a system and thus the range of possible functions. The features are determined by the user-specific software implemented. Due to the advances in microprocessor technology, it has for the first time been possible in the C450 mobile radio system to combine radio and call processing equipment with the high data processing capacity of microprocessors.

The commissioning of such computer-controlled transmission systems differs in several essential aspects from that of conventional systems, since the emphasis is no longer on the alignment of the hardware alone, but on the functional testing of the base station in relation to the system overall. Adjustments and modifications to the local system parameters during commissioning are always effected by changing the system data in the software. An operation and maintenance terminal (OMT) provides the system operator with the opportunity of reading or printing out the station-specific file during operation of the base station.

Some of the parameters can be modified from the OMT by means of menu-driven input commands to meet operating requirements, e.g. once operational experience of traffic characteristics has been gained.

The commissioning of a digitally controlled mobile radio network takes place in the following stages:

- Check of the manner of installation and the type of hardware in the base station,
- Power supply check,
- Check of clock and transmit signal distribution,
- Performance of radio system measurements,
- Testing the antenna system,
- Software function tests,
- Integration of the base station in the synchronous network,

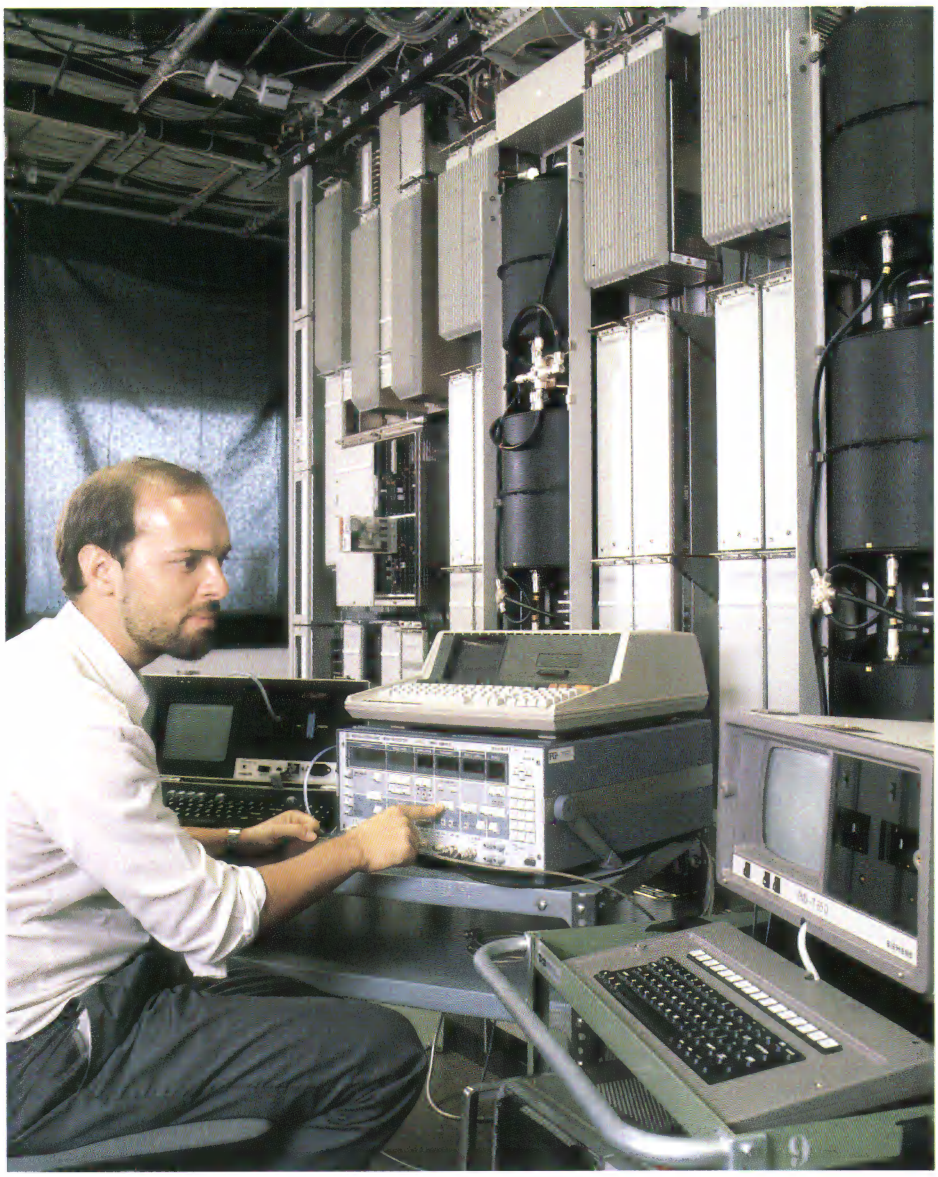


Fig. 3 Alignment operations in a base station

- Testing the interface between the base station and the mobile switching center,
- System function tests,
- Measurement of the coverage area.

Radio measurements

It is logical to use computer-controlled test equipment for the commissioning and maintenance of a computer-controlled mobile radio system. For the test equipment described below, Siemens has developed a test program which defines the sequence and extent of radio system measurements and which displays the test data on a monitor and prints out a listing. The test equipment comprises a radio test setup, a control computer with monitor and printer, a matching transformer and a test interface (**Fig. 3**). Measurements can be performed either automatically in a sequence or individually, the computer being used both for selecting the operation mode of the radio equipment and for controlling the test routines of the test setup.

A test interface module which is inserted in the *radio modem* unit of the base station enables all radio modules and units (transmitter power amplifier and RF link monitor) to be isolated for control purposes from the radio channel controller modules in the modem. This permits the computer linked to the test interface to select all operating modes of the radio section, such as frequency programming, voice and data operation and to test all other interfaces between the

radio section and the radio channel controller.

The following measurements are performed when commissioning the radio section of a base station in the C450 mobile radio system:

- Measuring the radio channel transmitters,
- Measuring the transmit frequency,
- Measuring the unweighted and weighted noise voltages,
- Measuring the VF distortion factors,
- Measuring the VF levels and frequency responses,
- Testing the speech scrambling,
- Testing the transmitter monitors,
- Measuring the frequency deviation,
- Testing the interfaces to the radio channel controller,
- Measuring the radio channel receivers,
- Measuring the receiver sensitivity,
- Measuring the attenuation of the RF cabling from the radio tester to the radio channel receivers.

Software function test

In order to check the operation of the control processors in the individual base station facilities, which are assigned to the function complexes call processing, radio processing, safeguarding and administration, the exchange of messages between the base station and the mobile switching center must be simulated. For this purpose, special test software is used instead of the standard operating software in the standby (inactive) signaling link interface (two of which are provided in the base station for increased reliability). This enables the signaling link interface to simulate the mobile switching center. The active and standby signaling link interface are interconnected on the line side and the lines to the mobile switching center are disconnected.

Instead of the mobile switching center, the simulator then responds to the messages sent by the base station with acknowledgements which are defined in a test list contained in the test software of the simulator. This test list can be adapted to all software tests for the function complexes call processing, safeguarding and administration of a base station by means of appropriate software modifications. The sequence of operations between the central processor, the base station control unit and the radio periphery on the one hand, and the mobile switching center on the other, can be followed by connecting a monitor to the interface processor of the base station control unit and can be output via a printer. Base stations can thus be fully commissioned completely independently of the mobile switching centers.

Integration of the base station into the synchronous network

Once the software function test has been successfully completed, the base station is integrated into the synchronous network by the *base station synchronizer*. All radio data, such as field strength, phase jitter and delay, which are of relevance to network synchronization, are stored in memory locations by a processor in the base station synchronizer. The contents of these memory locations can be read out and displayed in hexadecimal form on a monitor by means of a process tracer connected to the processor board of the base station synchronizer via a diagnostic connector. These data can also be output via a printer.

These hexadecimal data of the synchronizing signal must lie within specified tolerances, if the base station synchronizer and the synchronous network are functioning correctly. The evaluation of these radio data can result in a change, not only of the parameters in the base station file, but also in the structure of the synchronization chain, e.g. a change of the relevant reference base station.

Testing the interface between the base station and the mobile switching center

Before a base station can be connected to the associated mobile switching center, the VF lines and, above all, the

Fig. 4 Portable test setup

data lines must be tested with a data line analyzer, and their characteristics, such as level, frequency response, noise level and group delay distortion must be measured. To ensure interference-free exchange of messages between the base station and the mobile switching center, these data must also lie within specified tolerances.

After successful completion of the line measurements, the base station is connected to the associated mobile switching center and selected functions of the *call processing* and *administration* function complexes are tested once again from the base station and the mobile switching center. Here again, the sequence of operations between the central processor and the base station control unit and the radio periphery as well as the mobile switching center can be followed by connecting a monitor to the interface processor of the base station control unit and output via a printer.

System function test

The system function test is not restricted to one cell but extends across the coverage area of a mobile switching center. It enables essential system characteristics to be tested and serves to verify the reliability and availability of the radio network.

The test includes:

- *Off-air call setup*
Initiation of incoming and outgoing calls and allocation of channels according to radio criteria, such as field strength and jitter, via the control channel;

- *Queuing mode*
Seizure of all available voice channels in a cell;

- *Connection monitoring*
Maintenance of radio processing function and evaluation of voice signal quality on the basis of radio criteria, such as field strength and jitter, during the call;

- *Intracell handoff*
Changeover to another voice channel in the same cell in the event of cochannel interference – initiated by internal monitoring criteria;

- *Intercell handoff*
Determined by the relative distance measurement on crossing a cell boundary.

Two mobile test systems were developed for performing the system function test and recording all relevant radio data during operation. One test system is installed in a test vehicle and can be used for radio propagation measurements, system function tests and system maintenance by means of appropriate changes to the test software.

The other test system – the MC monitor – is a portable unit comprising an operating terminal and data processor (**Fig. 4**). This MC monitor is designed for mobile use in a car and can be powered from the automobile battery (12 V/ 1.8 A).

The data processing monitor is connected to the mobile station via a processor and permits data to be read from the mobile station processor. These data provide information on the status of the relevant radio data and the voice channels used. The MC monitor uses exactly the same SAB 8085 microprocessor system as the integral computer and the mobile station. The monitor also has a liquid crystal display and associated controller, as well as a hexadecimal keyboard, a processor card, a keyboard control card and a power supply. The data link to the computer is via a V.24 interface. The MC monitor programs are so structured that they are largely self-explanatory by means of the input instructions at the bottom of the display.

The successful conclusion of the system function test guarantees both the system operator and the user a reliable and convenient mobile radio network with high availability.

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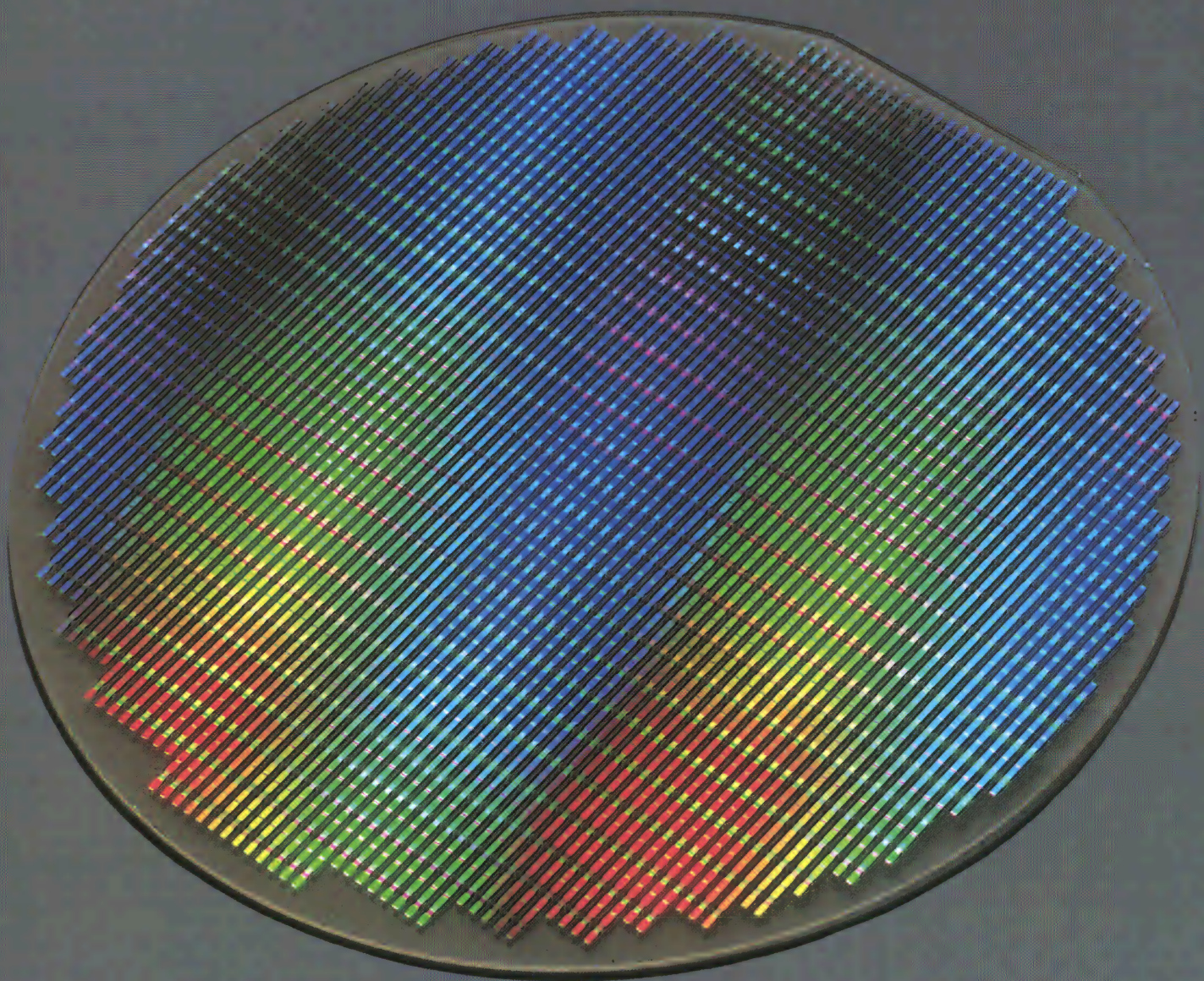

Reinmut Karl Hoffmann

Technology and Design of Microwave Components

For more than a decade, many of the microwave components used in radio relay, satellite and mobile radio equipment have been designed mainly in hybrid microwave integrated circuit technology. This technology permits economical manufacture and a high level of computer support in designing complex components in the frequency range from about 1 GHz to beyond 20 GHz. Typical of these components are multistage transistor amplifiers, transistor and diode oscillators, varactor frequency multipliers and single-sideband mixers. Conventional coaxial and waveguide components, on the other hand, are preferred for those requirements that cannot be met with integrated devices. Examples of these components are high-power circuits and steep-skirted filters.

Microwave integrated circuits (MICs) consist of planar conductor patterns on dielectric *substrates*. The most widely used type of planar waveguide is the *microstrip* transmission line which consists of a conductor strip on top of the substrate and a metallic ground plane usually covering the entire bottom surface of the substrate. Lumped elements, such as inductors, capacitors and resistors, can also be made of metallic films.

The electrical characteristics of the transmission-line components are determined by the dimensions and characteristics of the substrate material and of the transmission-line structures (details in [1]). For this reason, close tolerances must be applied to these technological quantities in order to ensure reproducible circuit characteristics.

In microwave integrated circuits a distinction is drawn between two types of technology, i.e. *monolithic microwave integrated circuits* (MMIC) and *hybrid microwave integrated circuits*. Whereas with MMICs all the components including the semiconductors are fabricated in the same technological processes on a semiconductor substrate (normally GaAs), the hybrid MICs nowadays used in radio relay equipment employ dielectric or ferrimagnetic substrates. Semiconductor components, such as diodes and transistors, and often capacitors and resistors, are connected to the coated and patterned substrate. The differences in construction require different assembly and interconnect technologies. Depending on frequency range, transmit power or complexity, different processes are used for fabricating the conductor patterns.

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Munich

◁ Surface acoustic wave (SAW) filters for commercial telecommunications are fabricated using the most modern photolithographic techniques. Pictured is a 3-inch quartz wafer with 1600 filter chips. The 1200 electrodes for one resonator have a width of only 0.8 µm each and must be fabricated to a precision of within a few hundreths of a micrometer in order to reproducibly guarantee the center frequency of 959.5 MHz and the bandwidth of 1.6 MHz.

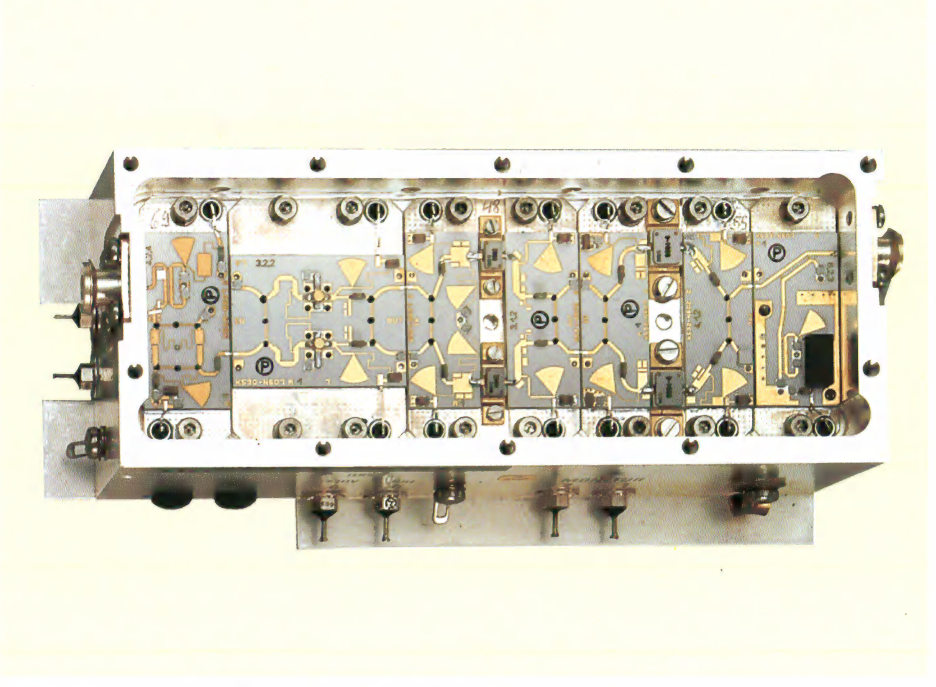

Fig. 1 Three-stage transmitter final amplifier with field-effect transistors for FM-TV/3500 radio relay system
(thin-film technology on 0.63 mm thick Al_2O_3 ceramic substrates; frequency range 3.4 to 3.6 GHz; gain typically 30 dB; saturated output power 4 W)

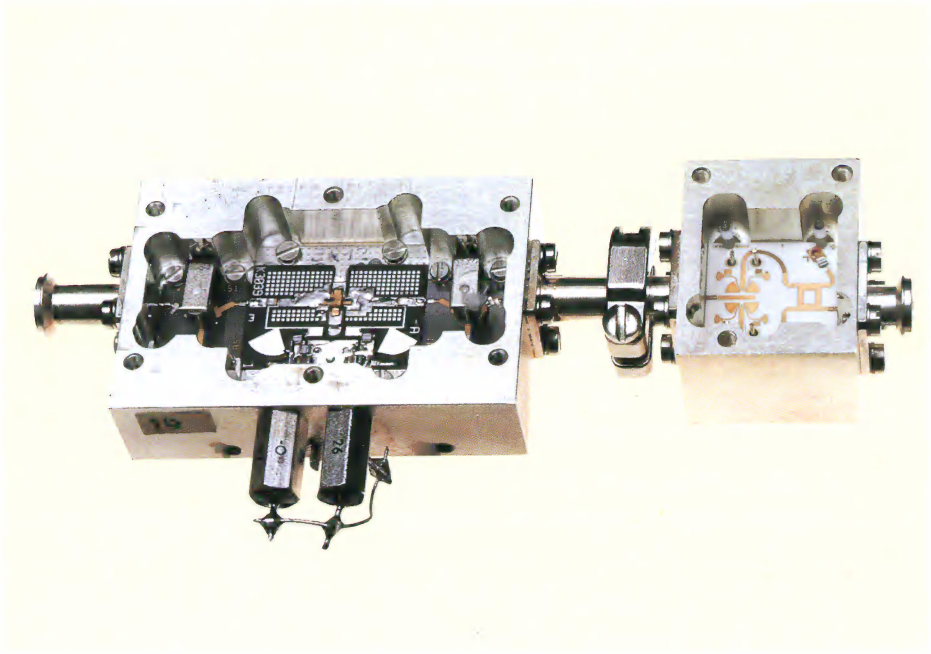

Fig. 2 Receiver front-end of DRS 140/11200 digital radio relay system
(field-effect transistor amplifier on copper-clad glass-filled PTFE substrate; two circulators in thick-film technology on garnet substrates; single-sideband double balanced mixer in thin-film technology on Al_2O_3 ceramic substrate; frequency range 10.7 to 11.7 GHz; gain typically 10 dB, overall noise figure typically 4.1 dB)

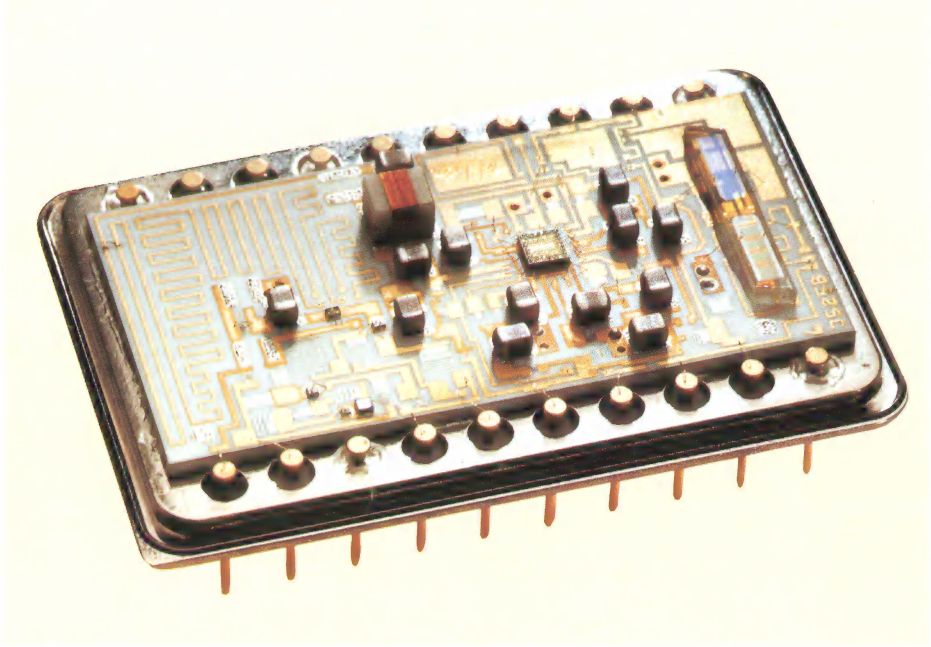

Fig. 3 SAW oscillator for digital modems
(thin-film technology with integrated resistors on Al_2O_3 ceramic substrate; frequencies established in the range 139 to 280 MHz by the SAW device; frequency stability about 2×10^{-4})

Typical circuits

Four typical examples of hybrid microwave integrated circuits serve to illustrate the different circuits possible and the configuration of microwave integrated circuits.

The *amplifier* reproduced in **Fig. 1**, a power component in modern radio relay equipment, replaces the traveling-wave tubes conventionally used for generating transmitter output power [2].

The *subsystem* shown in **Fig. 2** for a digital radio relay system [3] is an example of the way in which various technologies are combined to meet different circuit requirements. The circulators, for instance, with their relatively coarse structure were realized in thick-film technology, while the mixer with its fine structures was fabricated in thin-film technology [4]. The substrate employed for the amplifier was Teflon (polytetrafluorethylene or PTFE), the lower dielectric-constant permitting wider conductor paths with lower losses.

The *surface acoustic wave (SAW) oscillator* in **Fig. 3** shows an application for MIC technology at relatively low frequencies. In this device the meandered microstrip phase shifter is combined with an amplifier feedback circuit. The frequency-determining element is the surface acoustic wave delay line [5].

Fig. 4 shows various isolators as used to provide isolation between amplifier stages and matching at RF interfaces. Each of these isolators is a microstrip circulator with one port matched by a chip resistor termination. The two 3.8-GHz circulators equipped with a magnetic yoke as in **Figs. 4a** and **4b** employ different circuit designs for matching the resonator to the terminal lines (50-Ω characteristic impedance). If the $\lambda/4$ transformers of the conventional design (**Fig. 4a**) are replaced by a new lumped-element matching technique and the termination is connected directly to the third port without a $\lambda/4$ line as the complex conjugate match to the resonator, there is a considerable saving in substrate area (**Fig. 4b**). On the higher-frequency versions the yoke is omitted while retaining the same electrical characteristics to produce an even simpler configuration, so that the isolators can be freely located in larger circuit complexes (**Figs. 4c** and **4d**).

Fabricating the conductor patterns

The fabrication of development models and the subsequent production of released circuits take place in separate technology areas, each able to perform all technological operations. These include photomask production, substrate processing, substrate coating, pattern generation, trimming, hybridizing, sealing of components and packaging. In order to ensure that circuit development

is compatible with production capabilities, the Development and Production departments employ the same processes. Constant cooperation with the circuit development engineers provides a stimulus for improving the processes employed in the laboratory technology area. After a trial period these processes are then introduced into the production technology area.

The many different requirements placed on the microwave components of modern radio relay equipment imply the use of various types of technology for pattern generation. Accordingly, there are four types of pattern technology available (**table**). They differ as regards the substrate material employed, their suitability for fine or only coarse patterns, the »integrated elements« realizable in the particular pattern technology (e.g. conductor strips or resistors) and not least as regards the capital investment required.

The various *substrates* have a triple function in providing a physical support for the circuit, a waveguiding medium in conjunction with the transmission lines and film components as well as a technological medium for the film deposition and hybrid processes. This requires both stability against vibration, deformation and humidity stresses as well as low dielectric losses and minimum variation in the dielectric constant. Finally, the substrates must be compatible with all the technological processes. The thin- and thick-film technologies employ inorganic dielectric substrates, such as Al_2O_3 ceramic ($\varepsilon_r = 9.8 \pm 2\%$, $\tan\delta < 0.0001$ at 10 GHz), sapphire ($\varepsilon_r = 9.4$ and 10.6) or fused silica ($\varepsilon_r = 3.78$) and inorganic ferrimagnetic substrates, such as garnets (e.g. $\varepsilon_r = 14.3$) and ferrites (e.g. $\varepsilon_r = 12.9$). The most common is Al_2O_3 ceramic 0.63 mm thick (sometimes 0.25 and 1.27 mm thick). The ferrimagnetic substrates are primarily used for circulators and isolators. Organic substrates are also employed. These are generally Duroid or PTFE substrates ranging between 0.25 and 1.6 mm in thickness and incorporating glass microfibers or woven glass ($\varepsilon_r = 2.2$). In order to achieve the high levels of miniaturization obtainable with Al_2O_3 ceramic, ceramic powder is also incorporated in the PTFE to provide $\varepsilon_r = 10$. All these organic substrates are commercially available with rolled-on or electroplated copper cladding.

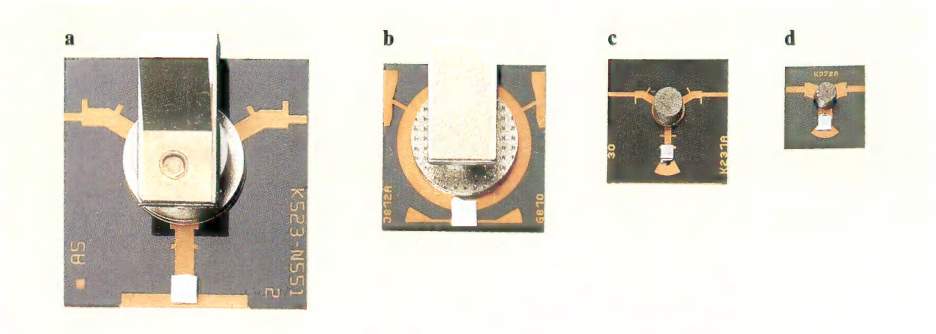

Fig. 4 Circulators connected as isolators for the radio relay frequency bands centered on 3.8 GHz (a and b), 11.2 GHz (c) and 18 GHz (d); thick-film technology on garnet substrates 1.27 mm thick (a and b) and 0.63 mm thick (c and d)

Technology	*Integrated components*	*Hybrid techniques*	*Film thickness*	*Minimum conductor width and spacing**
Thin-film hybrid technologies				
Copper conductor paths with protective gold plating	Conductors (copper)	Soldering Adhesives Bonding Alloying	8 to 17 µm	0.050 mm
Gold conductor paths and resistors	Conductors (gold) Resistors (nickel chromium)	Soldering Adhesives Bonding Alloying	5 µm	0.050 mm
Thick-film technology (for microwaves)	Conductors	Soldering Adhesives Bonding	8 to 16 µm	0.15 mm
Precision etching of copper-clad organic substrates	Conductors	Soldering Adhesives Bonding	5 to 18 µm	0.15 mm

* For volume production

Table The technologies customarily employed at Siemens for MIC components used in radio equipment

The *mechanical processing* of the *substrate* involves the use of special techniques. Utilizing the economies of scale, a large number of individual circuits are fabricated on a large common substrate. The substrates are separated by laser perforation (CO_2 laser, YAG laser) and subsequent breaking. If greater precision is required, a diamond saw is used. Via holes between the top and bottom of the substrate are formed with lasers or ultrasonic drills and sometimes with diamond drills or sandblasters.

Thin-film technology provides the finest line structures but the capital cost is high. Two approaches are available: one is to omit the resistors and fabricate the microwave circuit patterns with evaporated, reinforced copper conductor paths which are subsequently gold-plated. All the other elements, such as resistors, capacitors and semiconductor components, are applied subsequently. For circuits with many resistors (e.g. transistor amplifiers with integrated bias stabilization circuits) it is worth integrating the resistors also, but this approach is more expensive on account of the more complex layer structure. Both thin-film approaches permit via holes and are suitable for all the established hybrid techniques, such as soldering, bonding with conductive adhesive, microwelding (bonding) and alloying. The operations for fabricating the thin-film circuits are to coat the entire substrate surface with thin metal films by evapora-

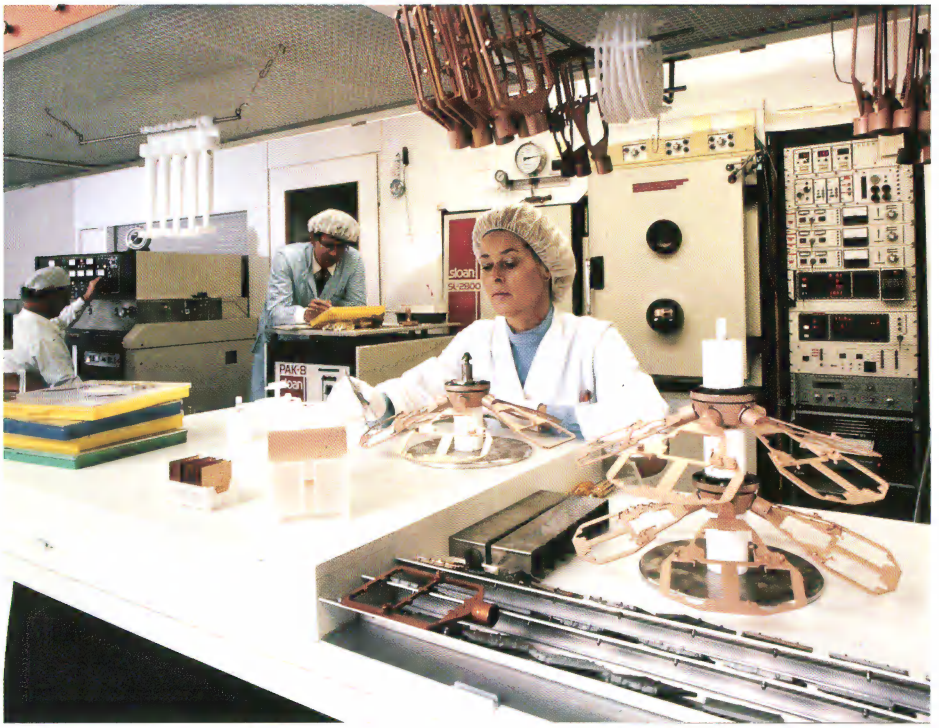

Fig. 5 Evaporation room in the laboratory technology area with several evaporation and sputtering systems

Fig. 6 Photoresist room in the laboratory technology area with exposure machine and photoresist roller

tion or sputtering in a high vacuum, followed by photolithography or photomasking. The line structures are then electroplated and the unwanted layer deposites are selectively etched. A view of the evaporation room in the laboratory technology area is shown in **Fig. 5**. In the photoresist room (**Fig. 6**), photoresist is applied to the coated substrates which are then exposed through the photomasks. **Figs. 1** and **2** (mixer) illustrate circuits with gold-plated copper conductor paths, **Fig. 3** a circuit with integrated resistors.

Circuits with less fine structures (e.g. circulators) employ *thick-film microwave technology* which provides more economical production and requires less capital investment. When copper pastes are used instead of the usual silver-palladium pastes, the microwave losses are just as low as with electroplated copper lines. The circulators shown in **Fig. 4** were fabricated in thick-film technology owing to their simple line structure.

Another way of manufacturing microwave integrated circuits is by *precision etching* commercially available copper-clad *organic substrates*. This technology is suitable mainly for simpler circuits with coarse patterns and a restricted range of hybrid elements (example: amplifier in **Fig. 2**).

Hybrid mounting and assembly technologies

When the substrate is available with the conductor pattern on it, the following processes must be performed before the circuit is complete: resistor trimming, component mounting ("hybridizing"), semiconductor component connection, packaging, functional trimming of resistors and conductor paths.

With the many different applications and complex circuit functions, there is an extensive range of hybrid devices available for modern microwave components. The range extends from simple ceramic chip capacitors through transistors in chip form or in transmission-line packages to low-inductance, superhigh-frequency semiconductor capacitors and millimeter-wave diode quads with extremely low-parasitic elements. A suitable range of *hybrid mounting techniques* must be provided. Bulkier components, such as ceramic and porcelain capacitor chips (single-layer, multilayer design), resistor chips, diode arrays and microwave transistors in transmission-line packages as well as inductors, are soldered into the circuits. Reflow soldering is the technique usually employed for this purpose. Complicated assemblies require step soldering in which the soldering takes place at different melting points. Unpackaged semiconductor components (semiconductor chips) are alloyed onto the gold conductor paths. A more recent alternative to soldering and alloying, which avoids excessive temperature stress, is bonding with conductive adhesives (e.g. epoxy resin

incorporating silver particles). The interconnections between the contact pads of the semiconductor chips and the conductor pattern, as well as between one part of the conductor pattern and another, are established using aluminium or gold wires (17 or 25 µm in diameter) or low-inductance gold ribbons (20 to 50 µm thick, 0.2 to 1.5 mm wide). They are connected reliably to the metallization surfaces by microwelding, thermocompression welding, ultrasonic welding and nailhead bonding. For larger circuits it is worth using self-learning, program-controlled bonders, an example of which is illustrated in **Fig. 7**. **Fig. 8** shows microwave structures shunted by a ribbon.

Resistor *trimming* is performed with program-controlled lasers (pulsed YAG or CO_2 lasers). The control tapes for this purpose are generated by a computer program which also designs the resistor layout. In addition to element trimming, many circuits require functional trimming in the fully equipped and operational state. This generally involves measuring microwave characteristics (e.g. gain/frequency response and noise figure of an amplifier) and trimming not only resistors but also the conductor paths of RF matching networks. There are different techniques available to suit the particular type of circuit. With one technique, metallized surfaces can be connected by bonding on wires, soldering on silver-foil bridges or applying conductive lacquer. With another technique, existing bonds are selectively opened. It is also possible to part conductor paths by laser.

When hybridizing is complete, the film circuit must be enclosed in a *metal package* – usually with coaxial *connectors* – for mechanical protection and electromagnetic shielding. A technological problem encountered at this stage is that of mechanically attaching the substrate to the package and of establishing the electrical connection between the substrate back metallization and the base of the package. This is accomplished with the aid of a spring-loaded press contact, surface soldering or surface adhesive bonding. The transmission lines are connected to the inner conductors of the coaxial connectors either by soldered or bonded ribbons or by press contacts. Strip conductor connections between adjacent substrates in the same package (**Figs. 1** and **2**) are established by welded, soldered or adhesive-bonded metal ribbons.

Fig. 7 Program-controlled bonder for welding bond wires on hybrid circuits

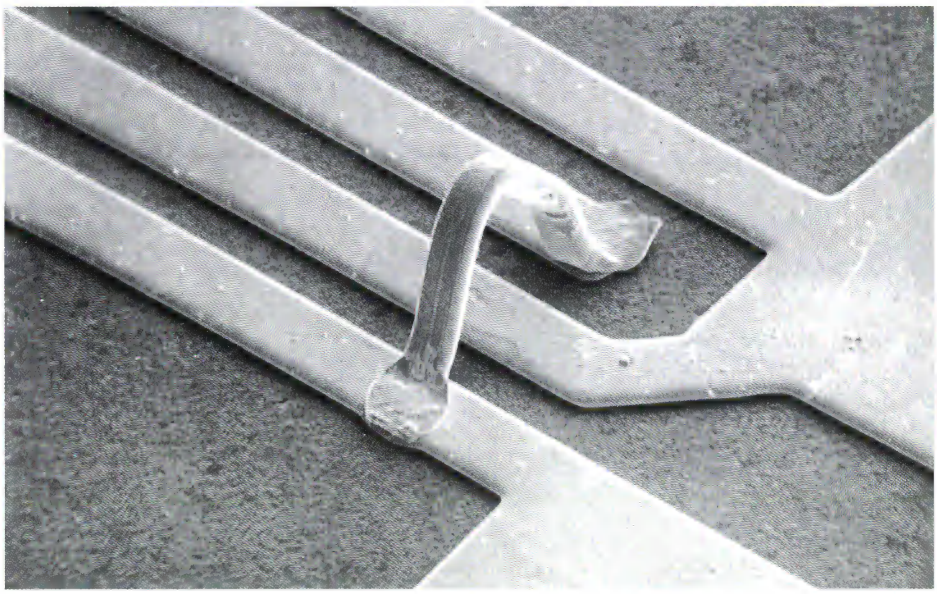

Fig. 8 Thin-film conductor pattern of an interdigital coupler with 40 µm × 20 µm bonded gold ribbons (conductor widths 60 µm; spacings 50 µm)

Modern microwave technology is making increasing use of *unpackaged semiconductor components* on account of the economic benefits and low-parasitic fringing reactances.

All the connection techniques described must undergo extensive reliability investigations before they are released to production. Examples of such investigations are high-temperature storage at +125 °C, temperature cycling between −25 and +125 °C, damp-heat storage at +40 °C and 95% relative humidity, various pull tests for soldered and bonded joints as well as gross and fine leakage tests for hermetically sealed packages.

Computer aided design tools

The development of a microwave component or module proceeds along the

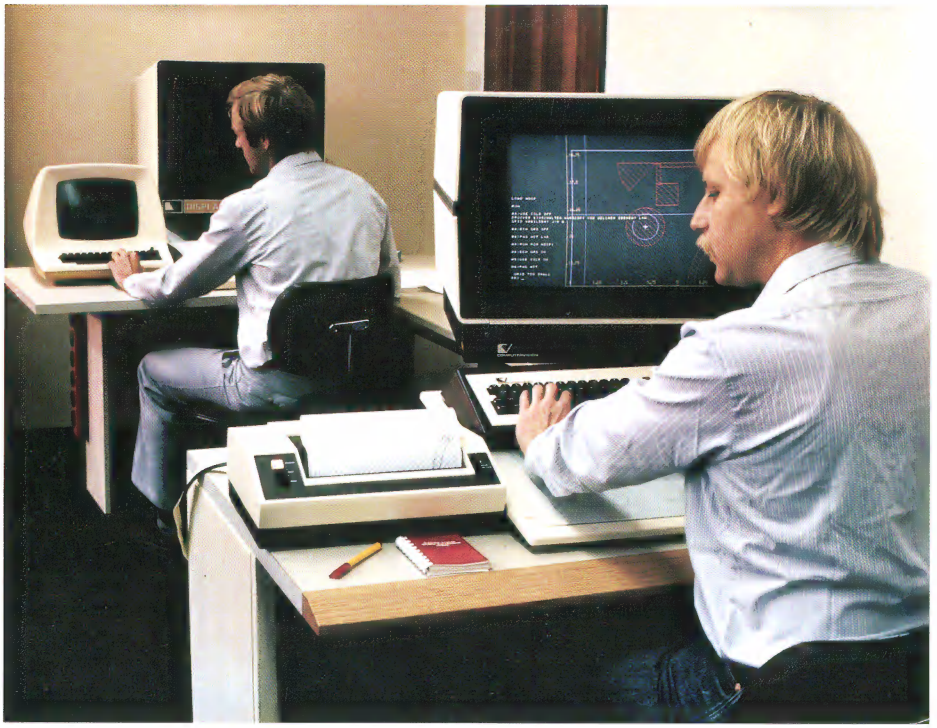

Fig. 9 Various VDU workstations for the computer-aided design of microwave integrated circuits

following simplified lines. The first requirement is to draw up the electrical and mechanical specifications, establish the basic circuit concept and select or specify the type of technology and the components. The cycle comprising "layout design → technological production of circuit models → test analysis of the circuit models" is repeated a number of times until the circuit meets the requirements. Finally, the fabrication documents are prepared. The aim is to reduce the number of cycles and the cycle time required, and to ensure on the basis of only a few circuit models the functionality of all the subsequent production circuits.

The systematic application of computer aided design (CAD) at all stages of circuit development enables development times to be reduced sharply while raising circuit quality. The following paragraphs summarize the CAD tools used for this purpose.

Computer aided pattern analysis

In order to predict as accurately as possible the radio-frequency response of a circuit implemented as a pattern of conductors, the precise electrical characteristics of all the building blocks making up the circuit pattern must be known over a wide frequency range. These building blocks include microstrip, slot and coplanar lines, finlines and suspended substrate lines, line discontinuities (bends, branches, crossovers, width changes) and lumped elements (spiral inductors, interdigital capacitors). They are calculated using computer programs ("pattern analysis programs") which employ numerical field calculation procedures.

Automatic computer aided testing

The hybrid elements (e.g. transistors) which are not covered by the pattern analysis programs are characterized on a wideband basis using computer-controlled network analyzers (frequency range 50 MHz to 26 GHz). Automatic testers of this type incorporate automatic measuring error elimination, user-specific measured-value conversion and frequency/time domain conversion. The test data are passed to network simulation programs for designing the overall circuit.

Network analysis and optimization programs

These computer programs permit automated design of complex microwave networks, the circuits being specified with simple formal data (e.g. node numbering). Pattern analysis programs are generally linked with or integrated in the network analysis programs so that patterns entered graphically on screen can be analyzed directly. Test data from the network analyzer are entered via data links or data media. It is possible, for instance, to calculate the transmission and noise characteristics or stability criteria and to optimize the circuits for these factors. Large volume simulation is possible using such techniques as tolerance, "Monte Carlo" and worst-case analyses.

Computer-aided photomask and control tape generation for production machines

When the circuits have been designed, models are made using computer-aided processes such as are subsequently employed in volume production.

The analyzed and optimized conductor pattern is entered in a mask drafting program on the color graphics screen. This program first checks that the technology-related specifications are met, then establishes the detailed layout of resistors (meander-line routing, trimming areas), designs trimming specifications and generates the associated control tapes for the trimming laser. It also produces control tapes for the laser to drill the holes for the vias in the substrate. The program then generates the control tapes for the computer-controlled mask drafting machine (1:1 scale pattern generator) which produces the technology-compatible photomask sets for fabricating the circuit.

Computer aided fabrication document preparation

The previously described computer program for photomask production can also be used for preparing fabrication documents for volume production. There is for this purpose a data link to component libraries and technical document management programs which are thus accessible to all production facilities at their various locations. The fabrication documents include, for instance, layout and hybridizing diagrams, parts lists as well as hybridizing, trimming, testing and inspection specifications.

Fig. 9 shows a room with computer terminals providing the laboratory area with access to the programs described.

Prospects

The thin- and thick-film hybrid technologies as well as the precision etching of copper-clad organic substrates have been employed for many years in the frequency range up to about 18 GHz and more recently at even higher frequencies. The technology is advancing towards a larger scale of integration (combining several components on one substrate to form "super-components") and a consequential introduction of unpackaged semiconductors with suitable passivation techniques for non-hermetically sealed circuit packages. In addition, the frequency range is being extended into the millimeter wave region (35 GHz) by the use of more suitable forms of lines (e.g. finline) and substrates (e.g. fused silica). The CAD tools for circuit design must be adapted to the resultant structures. In addition, the CAD models for many structures (e.g. discontinuities, lumped elements) must be improved and expanded to take account of higher frequencies. The introduction of a network of workstations in the development laboratories will permit further rationalization of development effort. With the quantities anticipated from satellite TV and from the introduction of communication systems operating into the Gbit/s range, monolithic microwave integrated circuits are assuming increasing importance alongside hybrid circuits.

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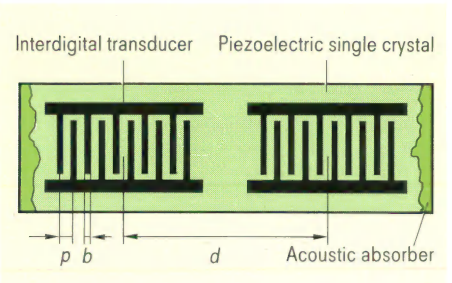
Gerd Riha, Helmut Stocker and Peter Zibis

Surface Acoustic Wave Filters for Digital Radio Relay Systems

Surface acoustic waves (SAWs) have enabled a microstructure-based filter technology for the radio frequency range, providing customized transfer functions of unprecedented precision and filters of incomparably high *Q*. Without these characteristics, modern digital radio relay systems cannot meet the demands for high spectrum efficiency and optimum transmission quality. SAW filters are used in these systems as spectrum-shaping IF filters, as delay lines in voltage-controlled oscillators for carrier and timing recovery and as resonators in stable oscillators for frequency conversion.

SAW filters in digital radio relay systems

High-capacity digital radio relay systems must transmit high bit rate signals over fixed radio frequency channels. For this application, quadrature amplitude modulation (QAM) has proved to be spectrally efficient. Its sin x/x-shaped amplitude spectrum, however, requires reshaping according to the Nyquist criterion. This can be achieved using filters with a cosine roll-off characteristic and a saddle-shaped pass band to flatten the spectrum. It is desirable that spectrum shaping be implemented in the IF band and distributed between transmitter and receiver [1]. This approach has been successfully adopted on 16 QAM systems using SAW technology to produce filters of the precision required [2]. In a radio relay system of this type, coherent demodulation is employed. The carrier and timing signals are recovered with phase-locked loops incorporating voltage-controlled oscillators (VCO). These oscillators can be optimally designed and manufactured with SAW delay lines to provide a high degree of stability at the high bit rates employed in modern systems. For frequency conver-



b Finger width
d Transducer center-to center separation
p Finger spacing

Fig. 1 SAW delay line

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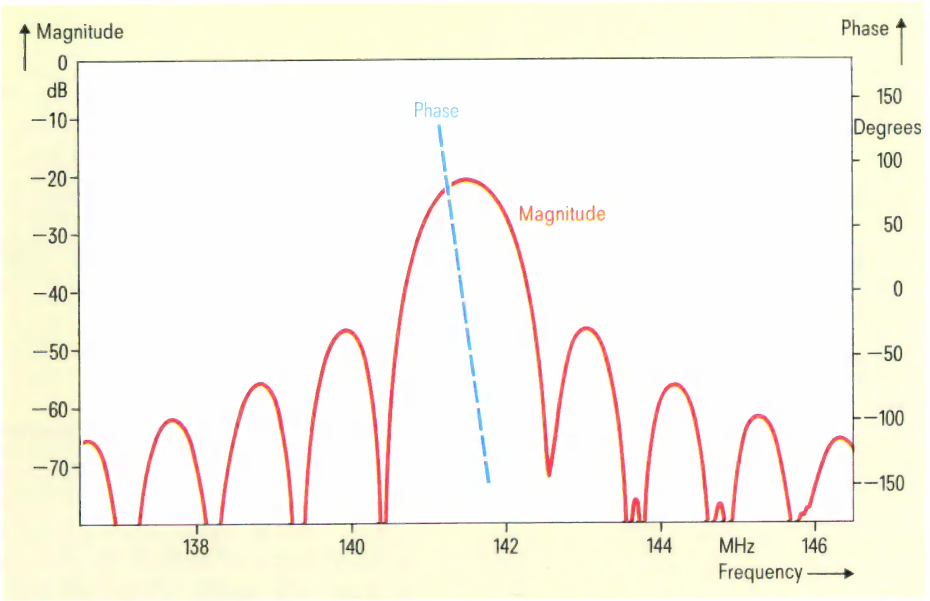


Fig. 2 Magnitude and phase of the transfer function of a delay line for timing recovery in a 140-Mbit/s digital radio relay system

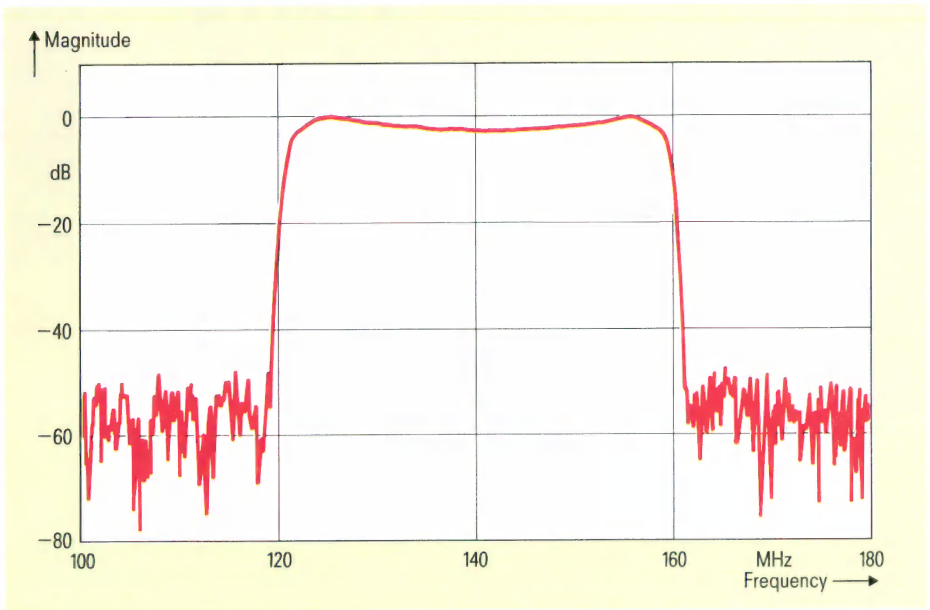
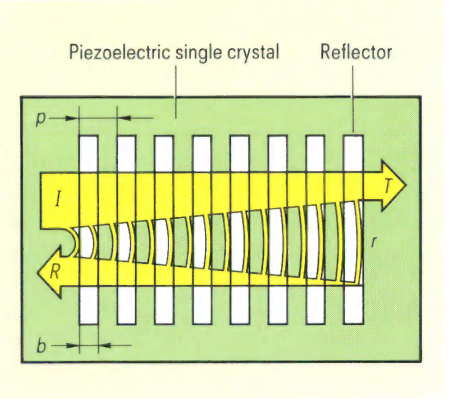


Fig. 3 Magnitude of the transfer function of a spectrum-shaping SAW filter for 140-Mbit/s digital radio relay systems



b Finger width
p Finger spacing
I Wave at input
r Portion of wave reflected at each finger edge
R Reflected wave
T Transmitted wave

Fig. 4 Operating principle of a SAW reflector

sion in radio relay systems, the SAW resonator can be used as a precision high-Q filter operating at frequencies of up to 1 GHz and providing oscillators with very low phase-noise power densities a few kHz from the carrier.

Basic principles of SAW filters

The operating principle of SAW filters is described in [3]. Even the simplest realization of a SAW filter (**Fig. 1**) offers sufficient design flexibility to allow its use as a "customized" delay line in stable voltage-controlled oscillators. The center frequency can be determined by the finger spacing and the filter bandwidth by the transducer length, the bandwidth narrowing as the number of fingers increases. The distance d between transducer centers and the propagation velocity v determine the delay $\tau = d/v$, which corresponds to the group delay and hence to the rate of change of phase. It should be noted that the free substrate surface between the two transducers produces a dead time which is undesirable in controlled oscillators. Consequently, the two transducers are generally located within only a few finger widths of each other, i.e. as close as the parasitic electromagnetic crosstalk will permit.

Owing to its structure, the input impedance of an interdigital transducer is highly capacitive, so that a resistive load results in a correspondingly large electrical mismatch. The insertion loss can be reduced via an external matching network. Since, however, the interdigital transducers produce bidirectional radiation, the minimum achievable insertion loss of a SAW filter is 6 dB, and interfering acoustic reflections occur. These take the form of a signal with three times the delay of the main signal (triple transit signal). The interference due to these two signals produces a ripple in the pass band of the filter.

If this ripple is to be limited, the transducers must be matched only to a certain

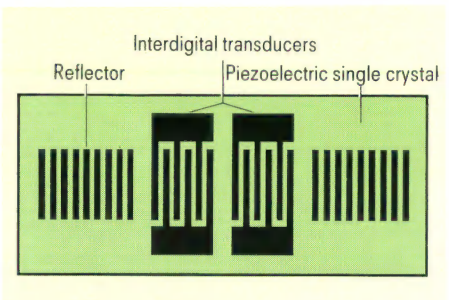


Fig. 5 SAW resonator

degree. The reflection suppression corresponds, in a first approximation, to twice the insertion loss. Generally, the insertion loss is therefore between 10 and 25 dB as typified by the delay line in **Fig. 2**.

The first sidelobes in the response curve of a delay line are suppressed by 26 dB relative to the main response. This degree of suppression is adequate for oscillator applications, but not for selective filters. For this reason, a transducer of a selective SAW filter has its finger-overlap lengths suitably weighted (Fig. 1 in [3]). The design concept is based on the idea that each transducer is basically a transversal filter structure. The delay of the wave between two fingers corresponds to the delay introduced by a delay section of a transversal filter; the finger overlap corresponds to a weighting factor. The large number of fingers which, due to the low propagation velocity of the surface wave, can be accommodated over a short length and the precise adjustment of finger lengths make it possible to produce filters with steep skirts and high selectivity. Finger weighting enables virtually any form of transfer function to be obtained (**Fig. 3**). It is possible to implement symmetrical and asymmetrical magnitude curves and constant or non-constant group delays.

The fingers of an interdigital transducer not only excite surface waves but also reflect them. The reflections are caused by the shorted tangential electric field and by the mass loading of the surface. The reflection behavior of a finger can be defined by a reflection from the front edge and a reflection of opposite sign from the rear edge of the finger.

If the transducer shown in **Fig. 1** is operated at frequency f_0, the wavelength of the surface wave is $\lambda = v/f_0$. The finger spacing required for maximum surface wave excitation is $p = \lambda/2$; however, this also means that the reflected waves add constructively. Although the reflection coefficient for each finger is merely a percentage, the reflected waves from the numerous fingers of a narrowband delay line would inadmissibly perturb its transfer function. For this reason, reflection-canceling transducer structures are used in practice. The best-known version, the split finger transducer, uses pairs of $\lambda/8$-wide fingers spaced $\lambda/4$ apart (Fig. 1 in [3]) instead of solid $\lambda/4$-wide fingers.

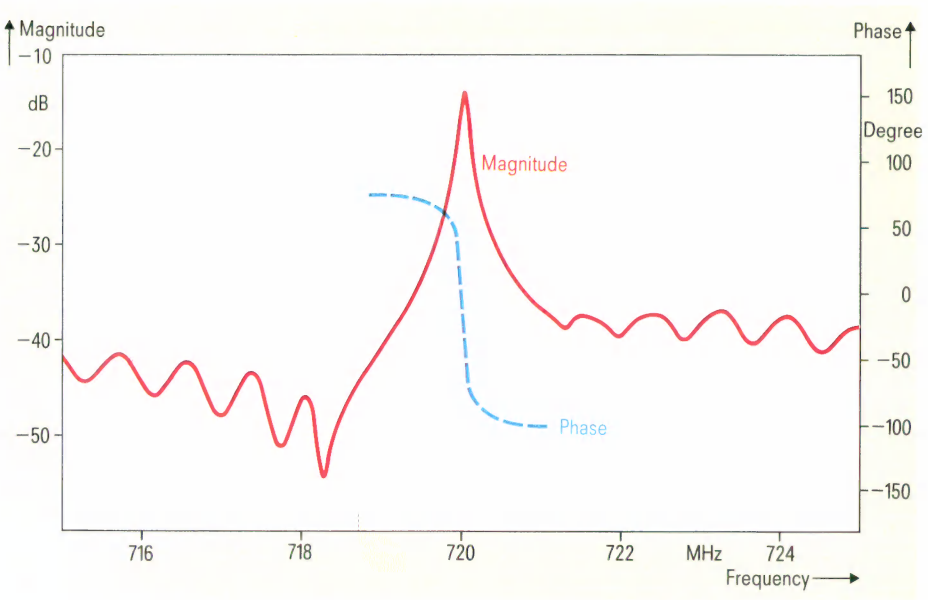


Fig. 6 Magnitude and phase of the transfer function of a resonator for frequency conversion in a digital radio system

The reflection property of a finger can be exploited to construct a reflector for surface waves. For this purpose, a few hundred b-wide fingers each displaced by $p = 2\ b = \lambda/2$ are deposited on the substrate surface (**Fig. 4**). This finger configuration provides almost total reflection of surface waves in a narrow frequency band.

The SAW resonator consists of two reflectors, spaced at an integral multiple of $\lambda/2$, and centrally embedded transducers (**Fig. 5**). At the center frequency

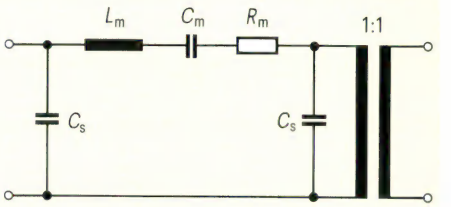


Fig. 7 Equivalent electrical circuit of a SAW resonator

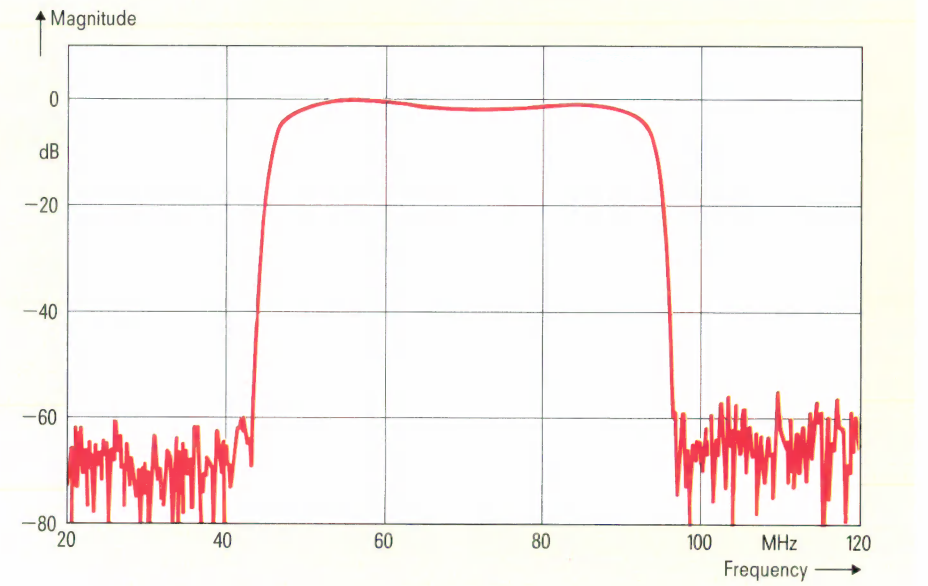


Fig. 8 Magnitude of the transfer function of a spectrum-shaping SAW filter with 74% relative bandwidth

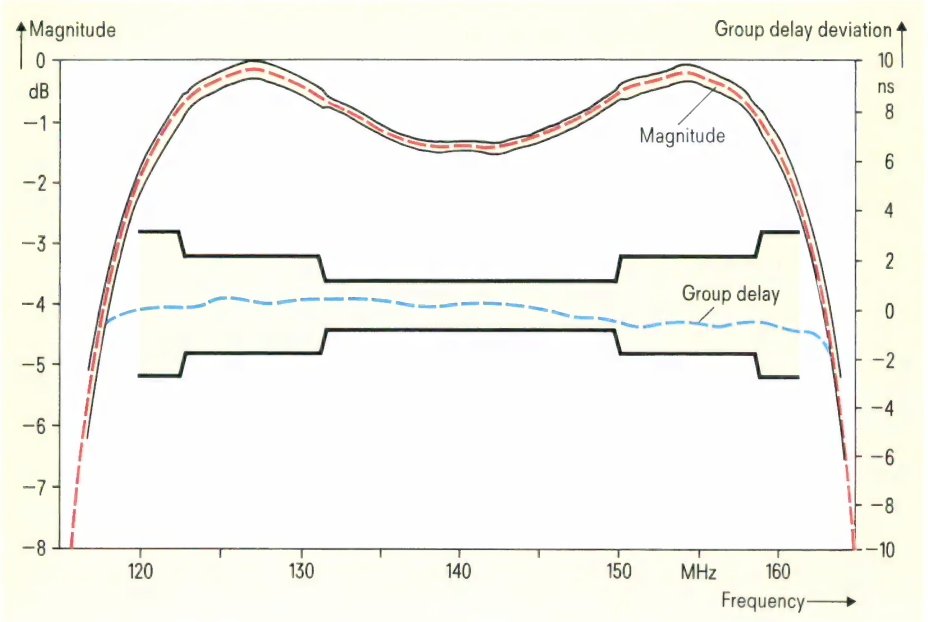


Fig. 9 Mean transfer function and tolerance diagram of a spectrum-shaping SAW filter for 140-Mbit/s digital radio relay system

f_0, this configuration shows an acoustic standing wave which creates the resonance peak in the resonator transfer function (**Fig. 6**). The response of the resonator at frequencies far removed from resonance is determined by the interdigital transducers. Close to the resonance peak, the behavior of the reflectors causes interference which accounts for the ripple present.

The resonance peak is determined by the Q factor of the resonator, which depends on inherent losses and on the electrical loading of the interdigital transducers. The Q factor of a loaded resonator is calculated by measuring the 3-dB bandwidth Δf or via the group delay τ, using the formula

$$Q_l = f_0/\Delta f = \pi \cdot \tau \cdot f_0 .$$

The Q factor of the resonator with unloaded transducers is Q_u. As it cannot be measured directly, it is calculated from Q_l and the associated minimum insertion loss I_l:

$$Q_u = Q_l \cdot \frac{1}{1-10^{\frac{-I_l}{20}}} .$$

The Q_u can be used conversely to determine the Q factor for any desired load.

The Q_u achievable using SAW resonators is approximately 5000 at 1 GHz and 20000 at 200 MHz at room ambient temperature. As the temperature increases, Q_u decreases by some 0.26% per Kelvin.

As the acoustic wave in resonators is enclosed between the reflectors, no bidirectional losses occur. With a suitable external electrical circuit, losses of less than 6 dB are achievable. The equivalent circuit in **Fig. 7** clearly illustrates the transfer function of a resonator within the 3-dB bandwidth. The series resonant circuit describes the acoustic standing wave, the two stray capacitances C_S being due to the capacitive behavior of the interdigital transducers.

Substrate properties

SAW technology places exacting requirements on the homogeneity and stability of the elastic and electrical properties of the substrate. Consequently, only single crystals are used. The most frequently employed materials are quartz, lithium tantalate and lithium niobate.

Of these materials, quartz stands out due to its temperature response. Its linear temperature coefficient of frequency is negligible, and the cut suitable

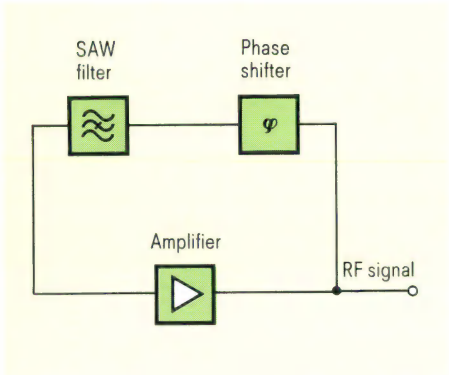


Fig. 10 Principle of a voltage-controlled oscillator with SAW filter

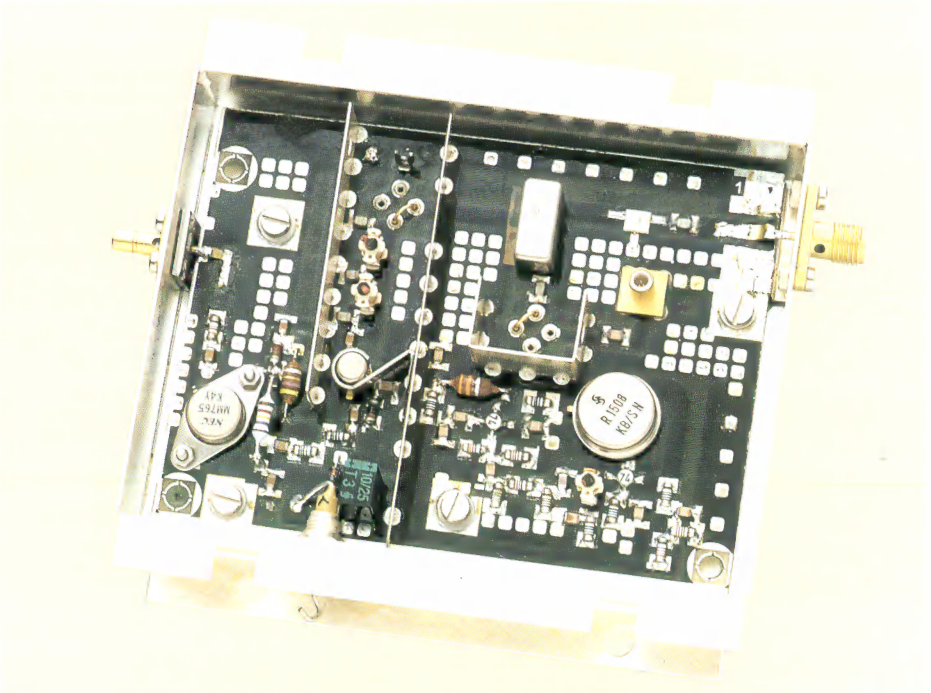


Fig. 11 Frequency converter with a 720-MHz local oscillator, comprising a SAW resonator in the TO8 package, an amplifier stage and a short transmission line section

for SAW applications has a parabolic temperature response of 0.03 ppm/K^2. The turning point of the parabola lies between −10 and 70 °C and can be set by selecting the cut angle of the quartz crystal. For temperature variations of ± 50 °C about the turning point, the center frequency of a quartz filter varies by only 75 ppm. A disadvantage of quartz is, however, the low electroacoustic coupling constant, which leads to high transducer impedances.

Larger coupling constants are provided by lithium tantalate and particularly lithium niobate. However, both materials have a linear temperature response (−18 ppm/K for lithium tantalate and −94 ppm/K for lithium niobate). Consequently, these two materials are preferred for wider-band filters.

The surface wave suffers propagation losses due to excitation of lattice vibrations (phonons) and attenuation of the acoustic wave by the atmosphere surrounding the substrate. These losses are taken into account by a Q factor for the substrate $Q_m = c/f_0$. At room ambient temperature and in a vacuum, the constant c assumes the value 10400 × GHz for quartz, and is even slightly higher for lithium tantalate and lithium niobate. This is the physical limit for the Q_u of a resonator.

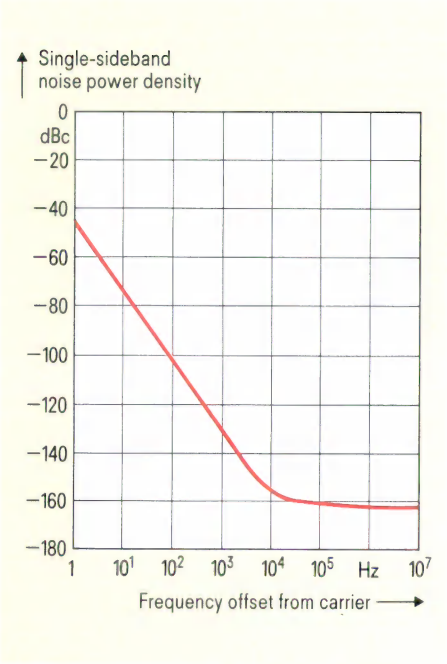


Fig. 12 Single-sideband phase noise of a 150-MHz voltage-controlled oscillator with SAW resonator

Spectrum-shaping SAW filters

Spectrum-shaping filters have to meet certain requirements which are demanding even for SAW devices. Depending on the bit rate, number of modulation states and IF band, the filters may be required to provide very large relative bandwidths combined with selectivity. The filter shown in **Fig. 8** with a relative bandwidth of 74% could only be developed using new computer-aided design procedures [4].

A spectrum-shaping filter with an imprecisely shaped pass band increases the bit error rate. Systematic deviations from the nominal transfer function can be minimized by a good design procedure. With a comprehensive computer-aided procedure, the finger structures of the transducers are designed by optimization methods, the SAW second-order effects are calculated precisely and the finger structure is modified to compensate for these effects [5]. However, the technological measures required to control tolerances are equally complex [3]. With the present state of the art, it is possible for spectrum-shaping SAW filters with the tolerance diagram shown in **Fig. 9** to be manufactured in volume. If the tolerances were fully exploited, this filter would cause less than 0.2-dB degradation of the signal-to-noise ratio in a 16 QAM system!

The precision required of spectrum-shaping filters increases with the number of QAM modulation states. In addition, even steeper skirts and enhanced selectivity are required in order to permit use of adjacent frequency bands. The roll-off factor of the steep-sided filter shown in **Fig. 3** is only 0.2 as compared with the 0.5 in **Fig. 9**.

SAW filters in oscillators

VCOs combining low-noise performance with temperature- and aging-stability can be implemented using crystal-controlled delay lines. **Fig. 10** shows the principle of a VCO. The phase shifter in this circuit is required to have a phase range of $\Delta\varphi$. In addition, the system requirements, temperature response and component aging call for a certain pulling range Δf. Phase range and pulling range determine the rate of change of phase and hence the delay and the distance between transducer centers of the delay line. However, for a delay line it is advisable to specify a Q factor Q_v corresponding to the delay

$$Q_v = \pi \cdot \tau \cdot f_0 = f_0/2 \cdot \Delta\varphi/\Delta f$$

rather than the delay itself. Once it has been set via the distance between transducer centers, the Q factor of the filter

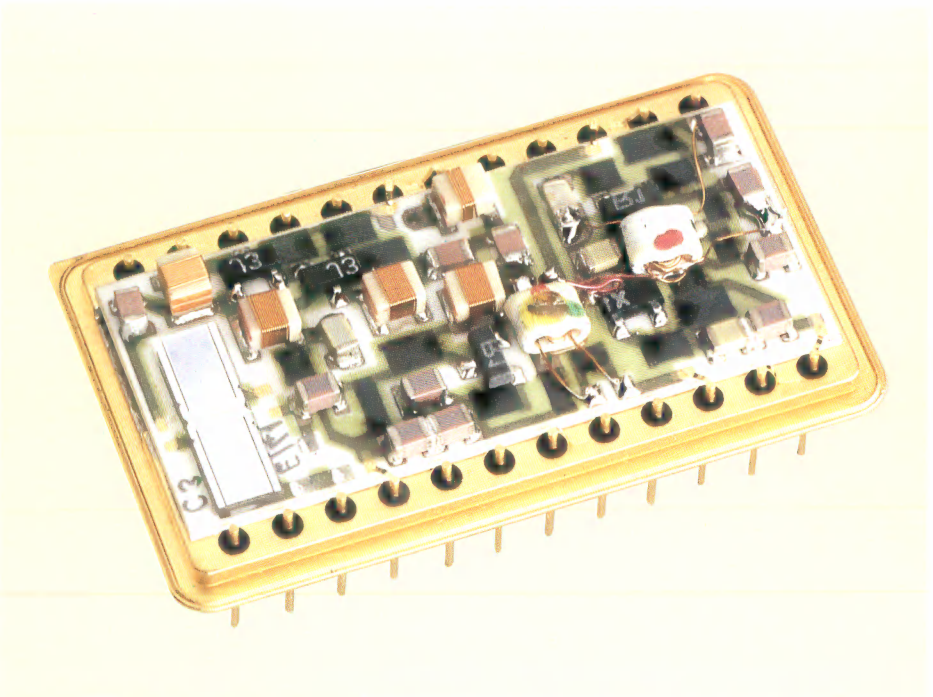


Fig. 13 150-MHz voltage-controlled oscillator with SAW resonator

remains unaffected by the external electrical circuit or aging. Delay lines offer the required flexibility for designing VCOs for carrier generation, carrier recovery and timing recovery [1] in digital radio relay systems.

A filter Q of 1000 corresponds to a transducer center-to-center separation of some 300 wavelengths. For higher Q factors, the space required by the delay line increases accordingly, and so resonators are used in preference.

Owing to their high Q factor, resonators are ideally suited for use as the frequency-determining component in oscillators for carrier-frequency generation. Whereas bulk quartz crystals are limited to low frequencies, it is possible to produce SAW resonators into the gigahertz range. As it is a standing wave that is generated in the resonator, its transfer phase is either 0° or 180°.

A compact oscillator is obtained by inserting a resonator in the feedback loop of an amplifier. As a result of the additional signal delay in the amplifier, the phase condition for oscillation is not usually satisfied. Consequently, the oscillator requires a phase shifter in the feedback path. This phase shifter may consist of a short transmission line section, as shown in **Fig. 11**.

An oscillator with high frequency stability requires a high-Q resonator. In order to ensure that the Q factor of the loaded resonator is not excessively reduced, the resonator must be operated under mismatch conditions. However, this results in a high insertion loss, just the reverse of what is required for a low oscillator noise floor. When designing the circuit, a compromise between these two conflicting requirements must be found.

With SAW technology the resonators can be fabricated with their impedances optimized for the particular requirement, thereby minimizing external circuit complexity.

SAW resonator oscillators provide an attractive alternative to oscillators employing conventional bulk quartz crystals and frequency multiplication. Whereas the latter are superior in terms of noise performance in the immediate vicinity of the carrier, aging stability and temperature response, the SAW resonator scores through the compactness of the circuit, the excellent single-sideband phase noise performance a few kilohertz from the carrier (**Fig. 12**) due to the wide dynamic range of the resonator, and through the absence of subharmonic signal components.

Very high quality oscillators are obtained by combining the concept of SAW resonator oscillators with that of bulk-crystal oscillators. **Fig. 13** shows a VCO with a SAW resonator as the frequency-determining component. If this oscillator is phase-locked to the frequency-multiplied signal from a bulk crystal, it is possible to exploit the advantages of both concepts.

Prospects

This article has shown that surface acoustic wave filters are now important components for high bit rate, spectrum-efficient digital radio relay systems. Systems implemented using these devices have optimum performance due to their high accuracy, and are extremely compact as a result of their miniaturized construction. They already meet the stringent requirements for 16 QAM and 64 QAM systems and will also be able to satisfy those of 256 QAM systems. There is also the possibility of using highly selective spectrum-shaping SAW filters to permit adjacent channel operation with the same polarization.

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Wolf-Eckhart Bulst and Evelyn Willibald-Riha

Reproducible Fabrication of Surface Acoustic Wave Filters

In the frequency range 10 MHz to 1 GHz, surface acoustic wave (SAW) filters have become established as key components in many modern radio transmission systems. SAW devices offer a high degree of design flexibility, permitting a wide range of applications in miniaturized, monolithic delay lines, filters and correlators. However, the great success of SAW technology is also attributable to the potential for ultraprecision fabrication of these devices by the latest photolithographic techniques. The reasons for this and the way in which Siemens is endeavoring to exploit this particular advantage of the innovative SAW technology are discussed from a production engineering point of view.

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Operating principle of SAW filters

Fig. 1 schematically illustrates the design of a typical SAW filter. It basically consists of a SAW chip attached and wire-bonded in a hermetically sealed package. The SAW chip itself is a piezoelectric substrate with a polished surface on which are deposited comb-like, interleaved metal structures, the interdigital transducers. When an electrical signal is applied to an interdigital transducer, an electric field is produced between the transducer fingers which are of opposite polarity. As a result of the piezoelectric effect, a mechanical distortion travels outwards like a tiny earthquake from each side of the transducer as a surface acoustic wave (**Fig. 2**). As the acoustic energy only penetrates into the substrate to a depth of about one wavelength, the surface wave propagates on the free surface, if well polished, without dispersion and virtually unattenuated. The wave traveling to the output transducer is converted back to an electrical signal which can be extracted at a load impedance. In order to prevent spurious signals, the portions of the surface wave traveling to the edges of the substrate must be attenuated by means of acoustic absorbers.

The SAW structure is shown in greater detail in **Fig. 3**. The transducer fingers with periodic spacing d select from the surface wave traveling at velocity v those electroacoustic signal components having wavelength $\lambda = 2d$ for which conditions of constructive interference exist. Signal components at other frequencies cancel each other. This provides the transducer configuration with a band-pass characteristic of synchronous or center frequency f_0 and bandwidth B (**Fig. 3c**). The shape of the pass-band curve is a function of the envelope of the finger overlap W in the transducer. This rectangular function (**Fig. 3a**) produces an equally rectangular acoustic impulse response (**Fig. 3b**) in the time domain and – via Fourier transform – a $\sin x/x$-shaped amplitude response in the frequency domain with a linear phase response. The product of the transfer functions of the two transducers yields the transfer function of the SAW filter as a whole (**Fig. 3c**). Therefore, in order to produce a desired frequency response in SAW filters, it is generally necessary to vary the finger-overlap length W of the transducers, i.e. to suitably weight the acoustic sources or sinks in their intensity [1] (**Fig. 1**).

Technological objective

The operating principle of SAW filters outlined above allows initial conclusions to be drawn about the precise and reproducible fabrication of these devices. If for reasons of cost the objective is to eliminate individual adjustment of each SAW filter, the production problem, as **Fig. 3** shows, is one of depositing metal gratings with precisely specified period d and length W on piezoelectric substrates of constant SAW propagation velocity v [2]. Siemens' experience indicates that this can best be achieved using highly-polished substrates of single crystal material and the photolithographic patterning process employed in the semiconductor industry. In geometrical terms, this approach could produce a positioning accuracy of 10 nm, i.e. a relative accuracy of 1×10^{-6} or parts per million (ppm) within an approximately 1 cm^2 field. This field is large enough to encompass typical SAW structures with frequencies above 300 MHz. In the case

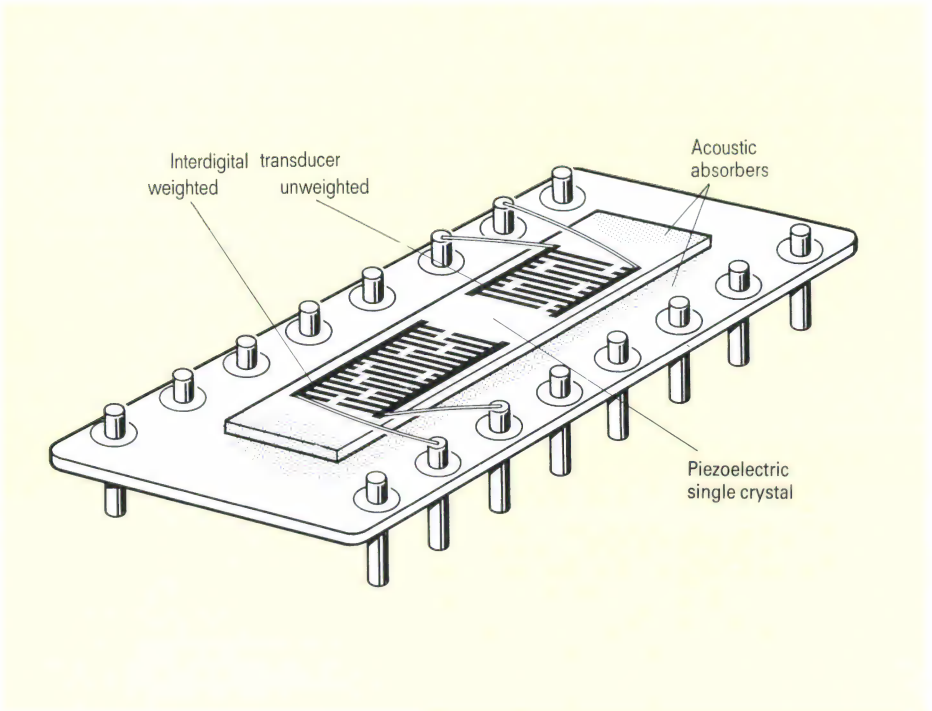


Fig. 1 Schematic arrangement of a surface acoustic wave (SAW) filter

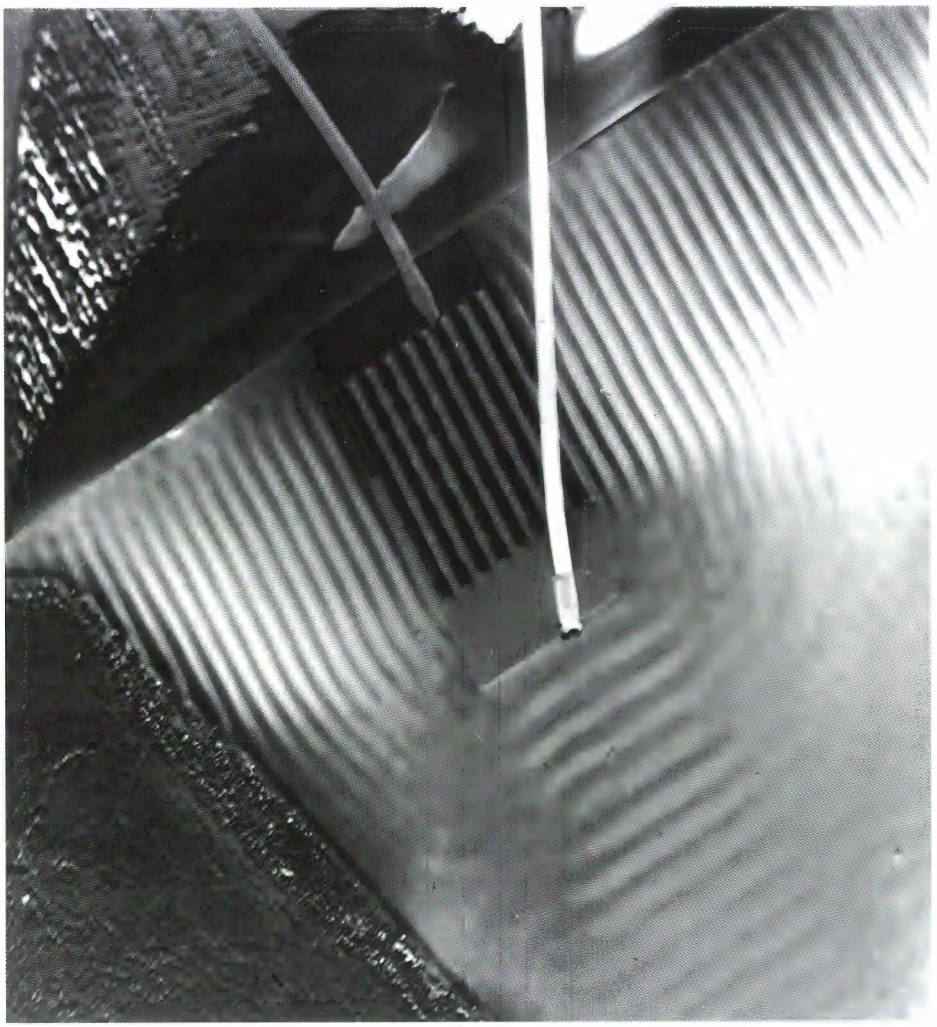
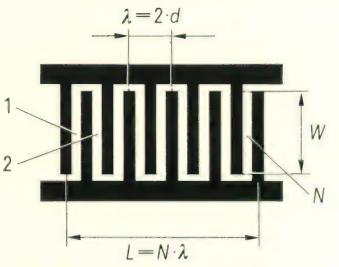
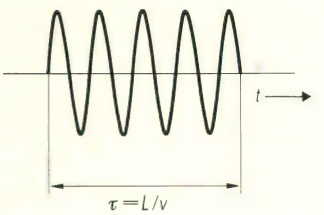


Fig. 2 Electron micrograph of a 36-MHz surface acoustic wave traveling out from both sides of an interdigital transducer, with a bulk wave excited by the pads propagating perpendicular to it

a

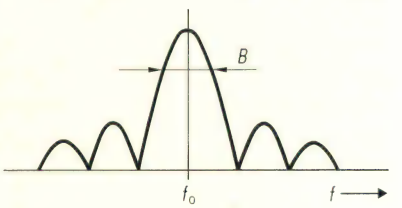


b



c

$f_0 = \frac{v}{\lambda} = \frac{v}{2 \cdot d}$ $B = \frac{1}{\tau} = \frac{v}{L} = \frac{v}{2 \cdot N \cdot d}$



d

Technological objectives	
$\Delta v \longrightarrow 0$	$\Delta d \longrightarrow 0,\ \Delta W \longrightarrow 0$
Minimum velocity variation	Maximum positioning accuracy

B Bandwidth
d Transducer finger period
f_0 Center frequency
L Transducer length
N Number of finger pairs
v SAW phase velocity
W Finger-overlap length
λ Wavelength
τ Duration of acoustic impulse response

Fig. 3 Technological objectives of SAW pattern fabrication

a Transducer geometry
b Acoustic impulse response
c Transfer function (band pass) of entire SAW filter with two transducers of type a
d Technological objectives

of larger-area SAW structures up to about 20 cm^2 overall and for frequencies between 10 and 300 MHz, a relative accuracy of around 1 ppm with 0.1 μm positioning accuracy is likewise possible using photocomposition techniques. At Siemens, the strategic objective of all design, development and production activities is to transfer the high fabrication precision inherent in SAW technology into the actual products. This highlights the main advantage over conventional LC or ceramic filters, which have a two to three orders of magnitude lower fabrication precision, are very much larger and require complex adjustments.

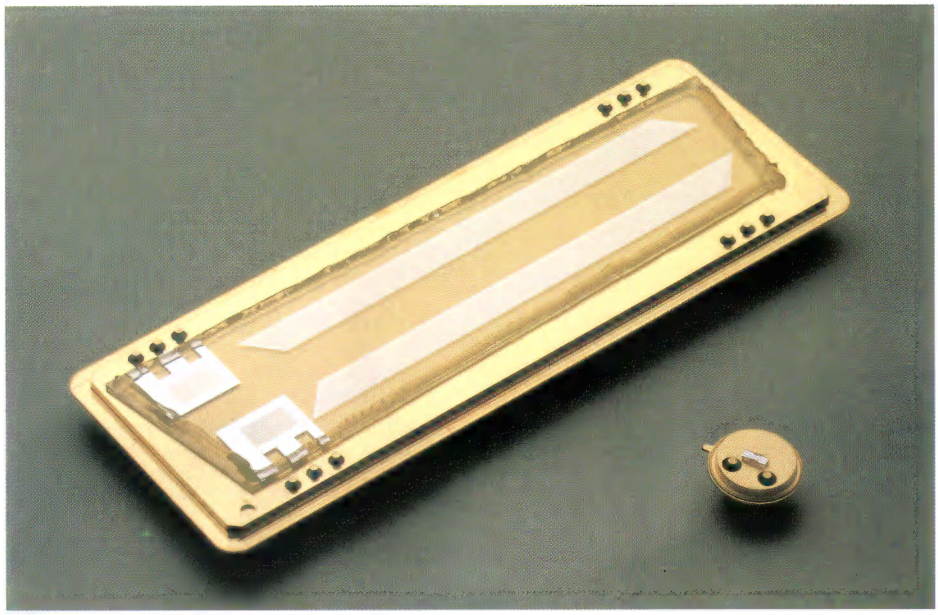


Fig. 4 Examples of the wide diversity of patterns and chip sizes of SAW devices
Left: 43-MHz pulse compression filter (chip size 15 cm^2; linewidth 9 µm; metal thickness 700 nm)
Right: 1-GHz resonator (chip size 2 mm^2; linewidth 0.8 µm; metal thickness 31 nm)

Technological concept

Owing to the versatility of SAW devices and the numerous special customer requirements, there exists a wide variety of structure patterns and chip sizes (**Fig. 4**). A requirement common to all these devices is that they should provide an optimum price-performance ratio or the highest performance in their class. In order to fabricate these devices properly for the widest possible range of applications, it is therefore necessary to adopt a suitable technological concept concentrating on the principal design similarities.

For more than ten years now, Siemens has been exploiting the rapid developments in semiconductor technology for application to SAW devices. These efforts have also persuaded material manufacturers in the USA and Japan to develop and supply 3-inch wafers as a suitable substrate material. Computer-controlled fabrication systems are used for the "cleaning," "resist coating," "exposure," "developing" and "metallization" processes. Optical (10:1) projection printing is an established fabrication method capable of providing the high resolution and positioning accuracy required as well as a low defect rate. Combined with an extremely simple single-layer liftoff technique, this method provides optimum dimensional control and pattern reproducibility with the smooth edges particularly important for acoustic performance.

The use of computer-controlled fabrication systems from the outset of research and development on the SAW devices ensures that all processes and results achieve a degree of reproducibility unaffected by the human factor. It also permits an evolutionary approach and rapid optimization of all the technological processes. There should not then be any serious difficulty in transferring these optimized processes from the development department to an identically equipped production facility.

Material selection

The basic requirement for reproducible fabrication of SAW devices is a virtually perfect substrate material. Only a flawlessly grown single crystal and a consistently good surface polish will ensure that the propagation velocity and attenuation of the surface acoustic wave remain constant. Constant SAW velocities additionally require very tight tolerances on the angles at which the wafers are cut from the synthetically grown single crystals. The wafer must meet extremely stringent requirements with regard to warp, taper and flatness, as it is important for precise optical imaging that the image field on the wafer surface should be precisely perpendicular to the optical axis of the (10:1) projection printing system [3].

As a result of intensive cooperation between Siemens and the material manufacturers, quartz wafers so far satisfy these requirements best. This is hardly surprising since quartz crystals, with their high temperature stability, have been traditionally used for fabricating particularly narrowband, i.e. precision, devices. The relative accuracy of the SAW velocity of currently available quartz material is therefore generally well below ± 100 ppm. However, lithium niobate ($LiNbO_3$) wafers, which are preferred for wideband SAW filters, delay lines and convolvers, have yet to meet these high accuracy requirements.

Pattern fabrication

Effect of linewidth and layer-thickness fluctuations

Variations in the pattern fabrication process affect both the SAW velocity v and the finger period d in the interdigital transducers. The relevant assessment criteria are the linewidth and layer-thickness fluctuations. Because of the following three effects, fluctuations in linewidth and layer thickness affect SAW velocity and hence the frequency precision of the filters:

- piezoelectric shorting under the transducer fingers,
- mass loading of the surface wave by the transducer fingers,

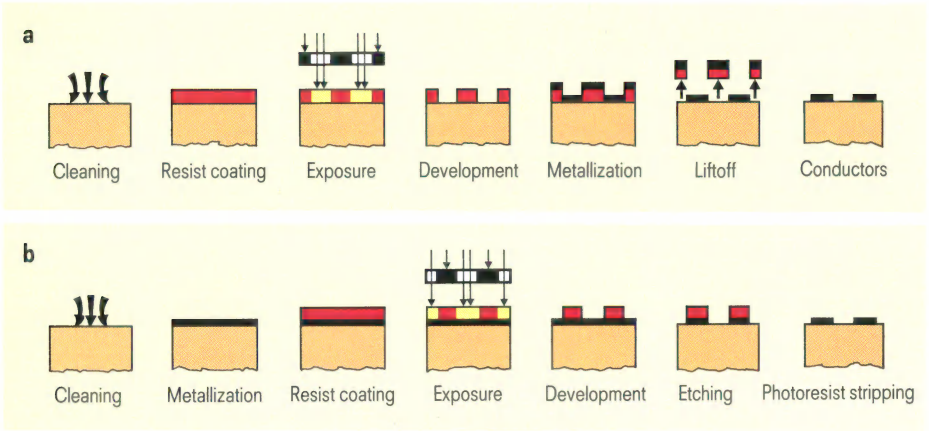


Fig. 5 Diagram illustrating the SAW patterning process

a Liftoff technique
b Etching

• mechanical energy stored in the finger edges.

For aluminium metallization layers with a thickness-to-wavelength ratio of 1%, 1-GHz transducers are estimated to provide a relative frequency accuracy of ± 13 ppm per 10 nm linewidth fluctuation on ST-cut quartz or ± 126 ppm on YZ-cut $LiNbO_3$. The fluctuations in aluminium thickness under the same conditions result in accuracies of ± 71 ppm/nm on ST-cut quartz or ± 85 ppm/nm on YZ-cut $LiNbO_3$. In the case of 100-MHz transducers, the frequency fluctuations are reduced accordingly by a factor of 10.

Finger period fluctuations

Fluctuations in the finger periodicity occur both during fabrication of the reticle which is scaled up by 10:1 and during subsequent imaging of the (1:1) pattern on the wafer. The reticle is produced on a pattern generator which flashes several rectangles (transducer fingers) through a pair of fully-programmable, high-speed aperture blades onto the photoresist-coated reticle which is moved along beneath the blades. Variations in the finger period therefore occur if the stages are incorrectly positioned. These stages are controlled by laser interferometry to a positioning accuracy of ± 0.1 µm. As this accuracy applies to any stage position and is always measured from the same origin point, the errors introduced during exposure of the fingers are not cumulative. As a result, the mean period error decreases as the number of fingers increases and is $\Delta d/d \leq \pm 32$ ppm for a 1-GHz transducer with $N = 100$ pairs of fingers. The same also applies to the accuracy of the bandwidth (**Fig. 3c**). Narrower-band SAW transducers, with their more critical center frequency requirements, contain more pairs of fingers resulting in correspondingly greater average positioning accuracy. Another variation in the finger period occurs during fabrication of the (1:1) pattern. The high-resolution projection printing systems (wafer steppers) used for this purpose have lens systems with a shallow depth of focus and therefore employ an automatic focusing system. Wafer thickness fluctuations, deviations in surface flatness and taper can be precisely compensated to ± 0.5 µm in the center of the image field. This variation in image width causes corresponding finger period fluctuations of around ± 9 ppm at each exposure.

Photolithography

The consistency of linewidth and layer thickness required for reproducible fabrication of SAW filters is achieved by means of a single-layer patterning process using the *liftoff technique* (**Fig. 5a**). The "cleaning," "resist coating" and "developing" operations illustrated are automated and performed on a computer-controlled photoresist processor. All the important machine and process parameters are closely controlled to ensure reproducibility of results. Exposure is effected by a wafer stepper.

This approach produces master mask quality directly on the wafer; linewidth fluctuations can only occur as a result of irregularities in the "resist coating," "exposure" and "developing" steps. After the latter, the photoresist on the wafer provides a virtually ideal mask. The subsequent process steps, "metallization" and "liftoff," (i.e. dissolving the photoresist e.g. in an acetone bath) are then unable to have any effect on the dimensional stability of the pattern. The patterns produced for precision SAW filters by the liftoff technique described exhibit linewidth fluctuations ≤ ± 0.03 µm within a wafer. Siemens' manufacturing specifications allow the linewidths of such wafers to vary by no more than ± 0.05 µm relative to each other.

This tight dimensional control of the pattern cannot be achieved using conventional etching techniques (**Fig. 5b**). As *aqueous chemical etching* invariably results in non-reproducible undercutting of the aluminum layer, the linewidth fluctuations are in this case at least ± 0.2 µm. As with *anisotropic reactive ion etching*, which provides some reduction in linewidth variations, aqueous chemical etching involves extremely corrosive agents – which impair the long-term stability of SAW filters. *Physical ion etching* destroys the crystal surface to a depth of approximately 10 nm. On 1-GHz resonators, which typically employ ion beam etched grooves instead of metal gratings as reflectors, this represents about 30% of the groove depth. However, a damaged layer of this kind will begin to anneal which in turn has a negative effect on device aging. With the *liftoff technique*, on the other hand, the wafers only come into contact with mild organic solvents which do not attack the crystal surface. The aluminum for producing the interdigital transducers and reflection gratings is deposited by an automatic electron-beam evaporation system equipped with a control system for indirectly measuring the layer thickness (quartz crystal). The thickness variations are about 1% of total layer thickness, the latter assuming any value between 20 nm for GHz filters and 700 nm for 43-MHz pulse compression filters (**Fig. 4**). If direct measuring instruments (profilometers) fail to provide sufficient accuracy, the actual layer-thickness fluctuations can only be estimated by recording the frequency reproducibility of these devices. If a sample wafer from

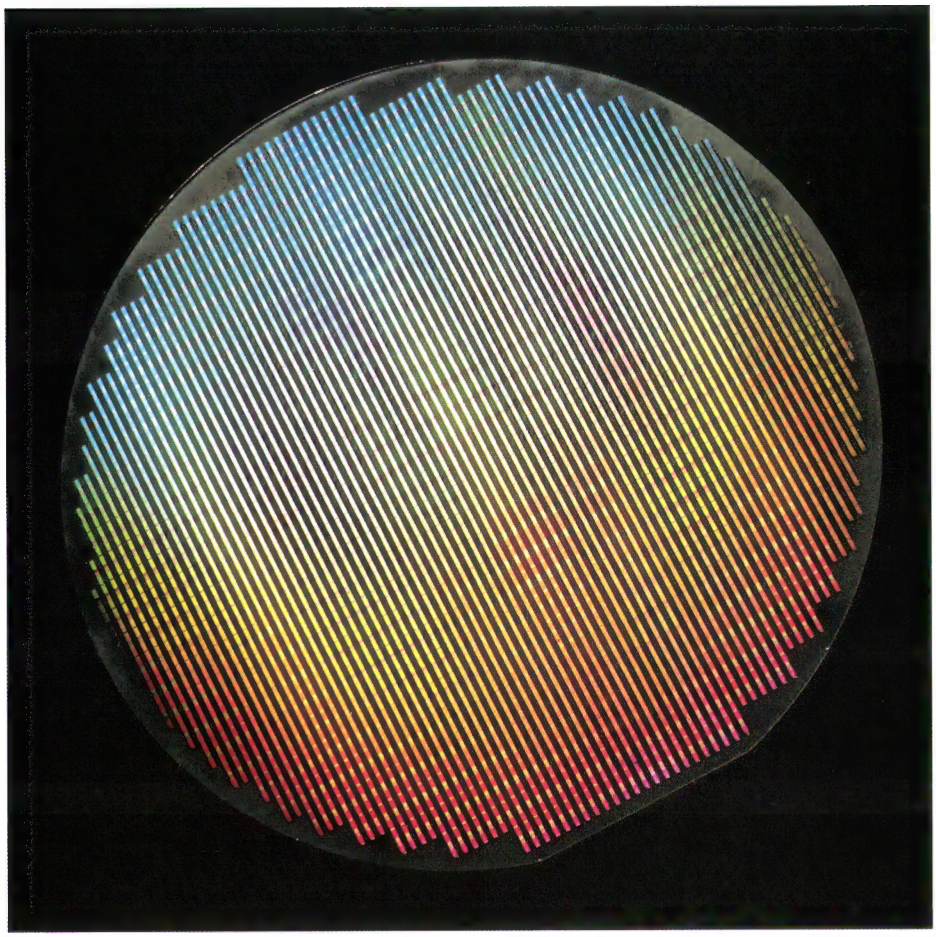


Fig. 6 3-inch quartz wafer coated with 1600 structures for 959.5-MHz resonator filters; the linewidth is 0.8 µm

a batch of identically processed quartz wafers deviates in center frequency from the desired target value, all the subsequent wafers already bearing the resist pattern are adjusted in frequency by altering the layer thickness accordingly. Measurements on a wafer prober indicate a typical frequency reproducibility of $< \pm 100$ ppm (3σ) within a given wafer of perfect material (or of $< \pm 300$ ppm overall) with line widths down to 1 µm ($\triangleq 800$ MHz). For higher-frequency filters (**Fig. 6**), the frequency variations increase since the specified resolution of the wafer stepper is only 1.25 µm. At lower frequencies, however, the frequency fluctuations may be significantly smaller.

Photocomposing

In addition to the high dimensional stability of the patterns, the liftoff technique offers a further advantage. The contrast employed in the patterning process is the reverse of that used for etching (**Fig. 5a**), i.e. the liftoff reticle has a light pattern on a dark background. Since this means that the surround always remains unexposed, it is possible for several small pattern sections to be exposed directly adjacent to each other by moving the resist-coated wafer under laser interferometer control. This process, known as *photocomposing*, is particularly suitable for exposing large-area SAW patterns requiring accurate positioning. The positioning accuracy on the wafer stepper is ± 0.1 µm. Many professional SAW patterns for band-pass filters up to about 200 MHz are composed of small pattern sections in this way. The procedure is to uncover each individual pattern section of the reticle in turn and then expose it on the correct wafer location using the appropriate degree of exposure.

For larger-area patterns it may be necessary to distribute the montage of small pattern sections among several reticles. This is extremely involved and increases the reject rate due to alignment errors; large-area pulse compression filters cannot be fabricated with adequate precision in this way. The wafer stepper therefore employs a direct-on-wafer pattern generation process comparable to electron-beam lithography. Unlike electron-beam lithography, however, this method provides the benefit of routine photolithographic processing with its excellent edge quality. The reticle contains all the elementary patterns required for composing the desired individual transducer pattern – e.g. long narrow rectangles for the transducer fingers, small rectangles for the gaps between fingers (weighting) and large-area rectangles for the pads. By varying the number of fingers (bandwidth), the finger spacing (frequency) and the finger-overlap length (weighting), it is possible to implement a large number of different designs, e.g. on only one wafer, using a single reticle. Alignment or positional errors >0.1 µm are now eliminated and sidelobe suppression for pulse compression achieves the theoretical limit values. In addition, the time-span of some weeks for each redesign during component development is reduced to a few days or even hours, i.e. the technology is capable of rapid response to customer requirements.

Chip mounting and final device testing

When the photolithography process is complete, the wafers receive a protective coating, are sawn off into chips using conventional semiconductor cutting methods and then cleaned. For some particularly critic devices it may be necessary to roughen the bottom surface of the wafer by sawing across it at selected points (dispersion of unwanted bulk waves), or to reduce the unwanted effect of bulk waves just below the surface by making a deep incision between the two transducers from the bottom of the substrate. The chips are then attached to the package bases, the SAW structures are interconnected with the package feedthroughs using standard bonding methods and the package is hermetically sealed in an N_2 atmosphere.

A SAW chip is an extremely sensitive detector of changes occurring in the environment (forces, pressures, contamination of a chemical or physical nature, temperature, etc.). Consequently, care must be taken when

mounting the SAW chip to ensure that the chip itself is in a highly stable state, that the microclimate in the package does not change even in the long term and that external environmental changes have no effect. If the user has a specific requirement for short-term stability (noise), temperature stability and aging, effective electromagnetic and acoustic feedthrough suppression, thermal and mechanical shock and vibration resistance or low-cost, low-volume products, this usually involves a tradeoff. The adhesives used for chip mounting or wave absorption (**Fig. 1**), for instance, must not outgas (aging) or stress the chip (frequency and temperature response), yet they must fasten the chip securely (shock and vibration). Special mixtures of epoxy, polyimide or silicone rubber are used to suit the particular mounting configuration (**Fig. 4**).

Once the packages have been sealed, all the devices undergo 100% electrical testing. This shows that the reproducibility of the transfer function, for high-Q SAW chips in particular, deteriorates only slightly if the chips are properly mounted. Temperature response measurements and accelerated aging tests [4] are only carried out on a sampling basis. These tests show that the complete SAW devices in most cases exhibit the anticipated temperature response of the substrate material and that precision devices can be expected to have annual aging rates of 1 ppm.

Prospects

The technological approach described in this article, involving the use of computer-controlled wafer processors in conjunction with (10:1) projection printing and liftoff techniques for reproducible fabrication of SAW devices, has yielded excellent results. The essential features of this approach are being transferred to a submicron processing facility representing the state of the art in equipment technology.

As a result of the excellent properties conferred by a highly sophisticated fabrication technology, SAW devices have become firmly established as delay lines, resonators and spectrum-shaping filters in communication transmission systems. They not only contribute significantly to cost-effectiveness and miniaturization in those applications, but they also provide the basis for implementing new and more sophisticated system concepts in the future. SAW devices will be employed in higher-frequency applications as filters with steeper skirts, lower insertion loss and even higher precision than before.

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Hans-Peter Grassl

Surface Acoustic Wave Convolvers for Spread Spectrum Radio Systems

In order to increase the interference protection for a radio transmission, the signals to be transmited can be provided with redundancy so that the wanted signal can be reliably detected in spite of interference. This leads to the use of wideband modulation techniques. With the spread spectrum technique, the signals to be transmitted are modulated with a very wideband spectrum-spreading function which is independent of the information content, e.g. a pseudorandom binary sequence (code) with a very high clock rate. In the receiver, the wanted signal can be very selectively detected by correlation with a locally generated reference code. This complex operation can be performed in real time in a surface acoustic wave (SAW) convolver by convolution of the received signal with the time-inverted reference code. In the device, the received signals and the reference signals travel toward each other as high-intensity acoustic waves on a piezoelectric substrate material and, in the region where they coincide, a nonlinearity causes the product of the two signals to be formed. This is extracted along the wave path as a spatial integral by a summing electrode. The resultant output signal is the convolution integral of the two input signals.

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SAW convolvers with a bandwidth of 200 MHz and a convolution length of 18 µs can be fabricated using standard technology for SAW devices on $LiNbO_3$ crystal substrates. With the aid of CAD techniques, the planar structures with which the acoustic waves are generated and guided are optimized such that the efficiency of the device (ratio of the output signal to the product of the input signals) is maximized and the phase and amplitude errors are minimized.

The acoustic convolver is currently the only fully programmable component which can correlate a phase-coded signal of only a few microseconds' duration with clock rates up to 200 Mbit/s. This allows radio signals to be transmitted in interference-protected bursts, e.g. in identification systems and radio networks using packet transmission techniques.

Correlation detection of coded signal formats in spread spectrum systems

According to C. E. Shannon's well-known formula

$$C = B \log_2 (1 + S/N),$$

the capacity C of a transmission channel for a given signal-to-noise ratio is a function of the bandwidth B. It follows from this that by increasing the transmission bandwith for a desired channel capacity at a given signal power, it is possible to achieve a considerable improvement in noise immunity. This relationship is exploited in spread spectrum systems [1]. Signals can be used whose bandwidth is many times that of the message to be transmitted. Unlike other wideband modulation techniques such as wideband frequency modulation (FM) or pulse code modulation (PCM), the bandwidth in this case is increased regardless of the content of the message to be transmitted. This ensures high quality transmission even at an extremely low signal-to-noise ratio ($S/N \ll 1$), as the receiver already knows the signal format.

Modulation and demodulation in a spread spectrum system are considered below with reference to the "direct sequence" method. **Fig. 1** shows the basic principle of a transmitter employing this method. The (digital) information to be transmitted is modulated with a high-clock-rate binary sequence (spreading code). Thus, one information bit may be

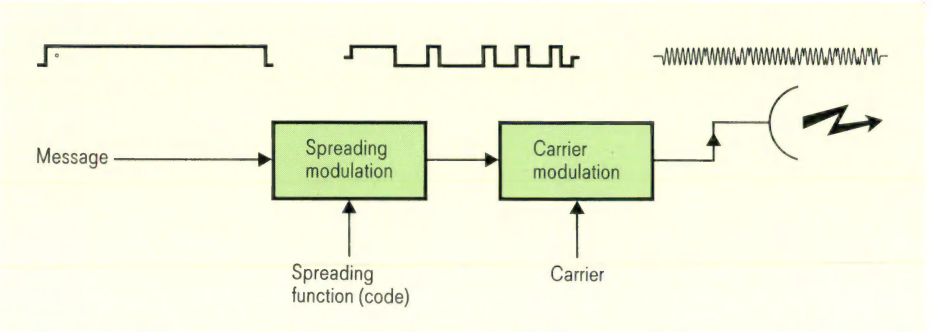

Fig. 1 Basic principle of a spread spectrum transmitter.
One message bit is encoded with a longer bit sequence, which is then impressed on a carrier

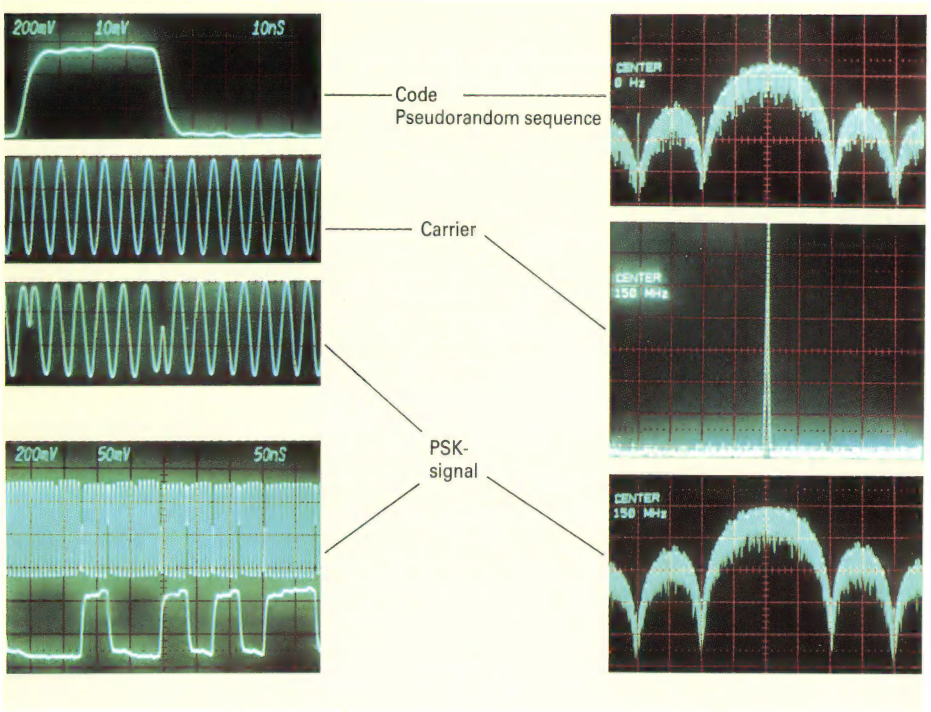

Fig. 2 Phase shift keyed (PSK) signal for spread spectrum communications. A high modulation rate in the time domain leads to a broad spectrum in the frequency domain. The phase of the carrier is switched in 180° steps

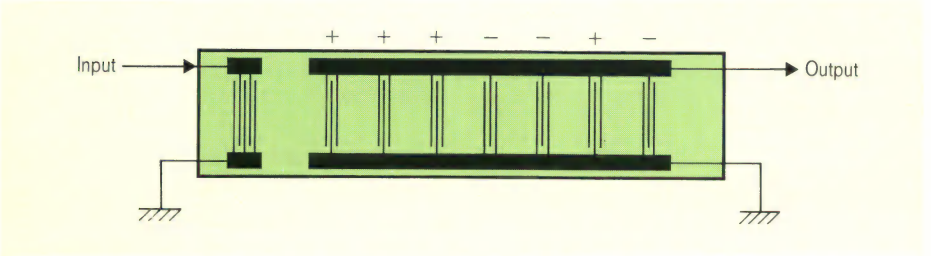

Fig. 3 SAW tapped delay line as a matched filter for PSK signals: the polarity of the finger groups in the output transducer defines the code

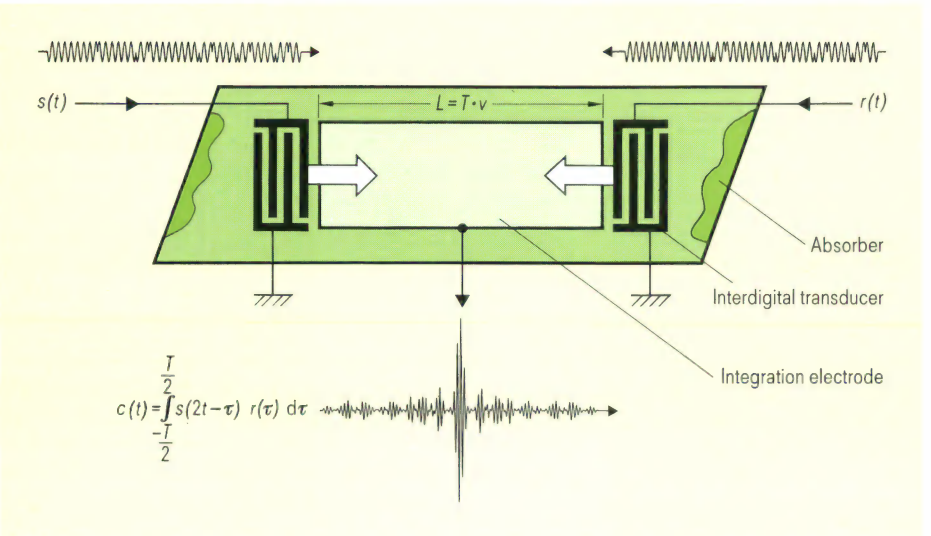

Fig. 4 Principle of the SAW convolver: two coded signals counterpropagate and interact under the integration electrode, resulting in the convolution of both

encoded with, for instance, a 1000-bit sequence, thereby increasing the bandwidth of the digital signal by a factor of 1000. This signal is then impressed on a carrier, e.g. as 180° phase shift modulation, and transmitted. **Fig. 2** shows the time response and spectrum of such a signal. Although the bandwidth required by these signals at a code clock rate on the order of 10 to 100 MHz is quite considerable, their spectral power density is correspondingly lower. In addition, with the signal being stochastic in nature, it is so unobtrusive as to permit multiple utilization of the band with the aid of various mutually orthogonal codes or even narrowband services coexisting in the same band. Further advantages stem from the fact that these signals can be used for accurate ranging and that fading due to multipath interference can be prevented.

Spread spectrum systems of this kind are particularly useful in applications where the transmission requires protection against interference, jamming and eavesdropping or must remain undetected [2, 3].

The receiver in a transmission system of this kind can simply reverse the process employed in the transmitter, i.e. the received signal can be modulated in an exactly inverse manner. As a result, the despread signal is recovered with the original bandwidth. By contrast, all the interference which is not correlated with the spreading function is again spread during inverse modulation in the receiver, and most of the interference can be separated from the wanted signal by means of a narrowband filter. However, the main problem of this demodulation technique is that the inverse modulation has to be precisely synchronized with the code contained in the received signal, to within a fraction of the clock period of the spreading code. Establishing this degree of synchronism for a signal of initially unknown arrival time involves a time-consuming search. This receiver principle cannot therefore be used where transmission is intermittent and only of short duration, e.g. in an identification system or a radio network employing packet switching [4].

This synchronization problem can be obviated by using a correlation receiver which correlates the received signal with the spreading code present in the receiver by means of a matched filter. As soon

as the code in the received signal coincides with the reference code in the receiver, a large signal peak appears at the output of the matched filter. This peak corresponds to the sharp maximum of the autocorrelation function of the code. Naturally, the codes used as spreading functions in a process of this kind will be those exhibiting a suitable autocorrelation response, such as *m*-sequences or similar pseudorandom sequences.

SAW technology is ideal for implementing the type of high-speed correlator required for correlation detection. The storage, shifting and multiplication opeations necessary for correlation can be easily performed using surface acoustic waves. Multiplication can be provided by the interaction of an acoustic wave with an interdigital transducer. For this purpose, the transducer must have a finger-overlap pattern corresponding to the code with which the received signals are to be correlated (**Fig. 3**). A very simple, passive device of this kind, a tapped delay line, can be used to perform a correlation with a certain, preset reference function. A major disadvantage, however, is that the reference function cannot be changed. A dedicated device must be fabricated for each code, and once a code has been selected, it cannot be reprogrammed. However, in a security-sensitive system, it is vitally important to be able to change the spreading codes in rapid succession. Similarly, a system with code-division multiplexing also requires a rapid code change.

A high-speed programmable correlator can be implemented with a SAW convolver. A convolver provides the convolution of a received signal and a second, externally applied signal used as a reference. Convolution with a function, however, is identical with correlation of the time inverse of the function. A digitally generated reference signal can also be easily produced in time-inverted form.

Mode of operation and design of a SAW convolver

Fig. 4 shows the basic scheme of a SAW convolver. Deposited at either end of the polished surface of a piezoelectric crystal substrate (lithium niobate) are two interdigital transducers for converting the signals, which are to under go convolution, into surface acoustic waves. These waves travel toward each other on a common path. Where the two waves coincide, a polarization component proportional to the product of the wave amplitudes is produced due to nonlinearity of the substrate. An elongated metal electrode placed on this zone spatially integrates the resultant polarization charges. Consequently, it can be used to extract a signal which, as a result of the continuous relative displacement between the two input signals, represents their convolution. It has the form

$$c(t) = C_0 \cdot \int_{-T/2}^{T/2} s\,(2t-\tau) \cdot r(\tau)\,\mathrm{d}\tau.$$

Compared with conventional convolution in the mathematical sense, the timescale in the output signal $c(t)$ is compressed by a factor of 2, the integration extending only over a finite range. The time compression is tantamount to doubling the frequency in the output signal spectrum. As the surface wave propagation velocity is approximately 3400 m/s, it is possible, for example, to process signals of some 17.6 µs duration over a length of 6 cm.

Owing to the very small nonlinearity of the elastic and piezoelectric material constants in the crystal substrate, a number of measures must be taken to maximize device efficiency. This is

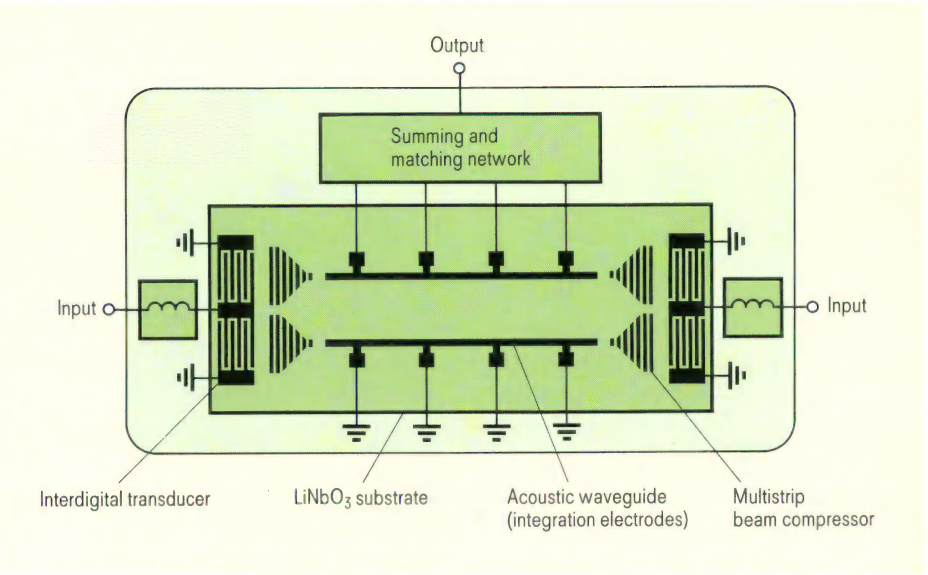

Fig. 5 Layout of convolver for optimizing efficiency and suppressing interfering effects

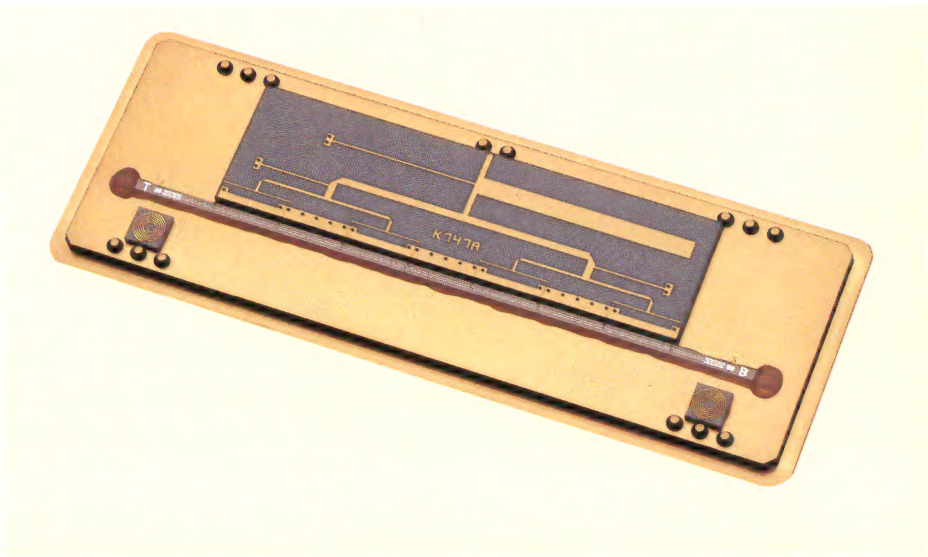

Fig. 6 Convolver with planar matching networks in hermetically sealable package; the $LiNbO_3$ chip measures 1.5 mm × 60 mm

defined as the ratio of the output power to the product of the input powers when sinusoidal signals of identical frequency are applied to both inputs. Consequently:

$$E(2f) = 10 \cdot [\lg_{10} P_c(2f) - \lg_{10} P_s(f) - \lg_{10} P_r(f)] \text{ [dBm]}.$$

In order for a convolver to produce an undistorted convolution signal, the efficiency across the bandwidth of the signals to be processed must, as far as possible, be constant in terms of magnitude, and linear in terms of phase against frequency.

High efficiency requires optimal electroacoustic signal conversion. This is achieved by good electrical matching of the interdigital transducers, which in turn places certain requirements on transducer design. In order to make the nonlinearity as highly effective as possible, it is necessary to maximize the acoustic intensity on the wave path. This is achieved by special focusing structures for the surface waves. However, as a concentrated beam with an aperture of a few wavelengths would immediately disperse due to diffraction, the acoustic wave must be guided through a waveguide over the long interaction section of a few thousand wavelengths. The metal strip required as an integration electrode acts as such a waveguide, since the waves have a slightly lower propagation velocity on a metallized surface than on the free surface.

However, a waveguide has various modes propagating at different velocities. Moreover, these modes are dispersive. It is therefore necessary to design the waveguide and the feedstructure such that only a single propagation mode is guided. Similarly, suitable measures are required to compensate for waveguide dispersion. Finally, the resultant convolution signal distributed along the length of the integration electrode must be collected from all points along the interaction section with equal weight and transmitted with equal delay by a matching network to the device output. The convolution signal components are able to propagate along the integration electrode as electromagnetic waves. However, due to the high dielectric constant of lithium niobate and the thinness of the acoustic waveguide layer, this signal propagation is heavily attenuated and dispersive. For this reason, signal taps wire-bonded to a summing network are provided at closely spaced intervals along the integration electrode. With a network consisting of microstrip conductors on an alumina substrate, it is possible to achieve the desired symmetry and matching characteristics.

Fig. 5 shows the diagram of a convolver optimized in accordance with the considerations outlined above. **Fig. 6** shows a component with planar matching elements in the package which can be hermetically sealed. The device contains two convolvers connected in parallel in a special way. The purpose of this is to suppress a very damaging interference effect, the self-convolution of an input signal due to acoustic waves being reflected from the opposite interdigital

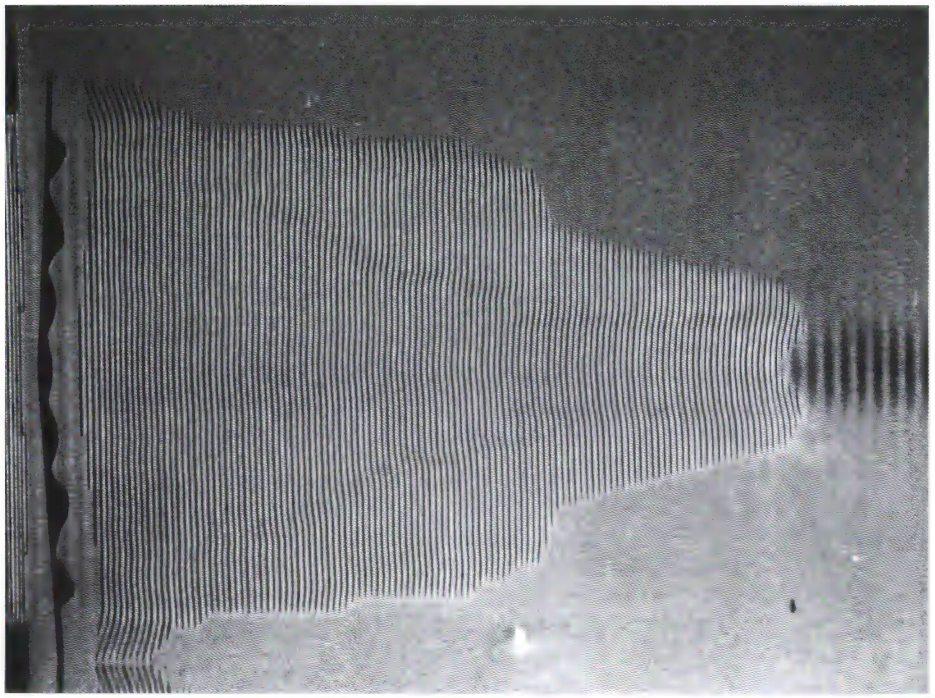

Fig. 7 Multistrip beam compressor in action.
The scanning electron microscope reveals the potential accompanying the surface wave

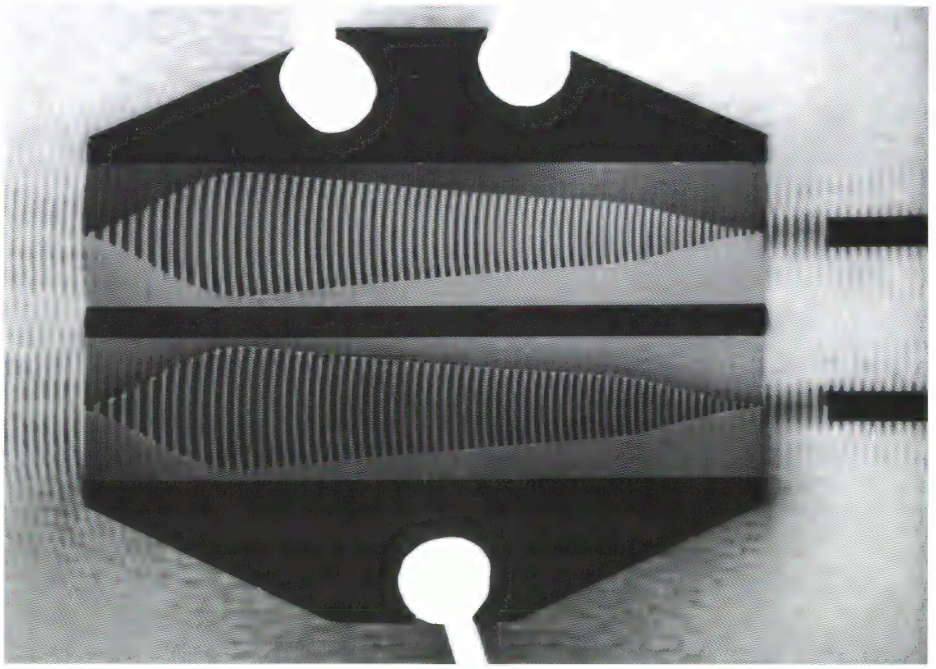

Fig. 8 Small-aperture transducers with curved fingers emit a well-focused acoustic beam (visible on the right-hand side of the photo) into the waveguide ends without beam compressors

transducer after passing through the interaction section. The transducers of the two parallel convolver sections are connected in parallel at one end and in inverse parallel at the other. The two convolution signals produced on the two integration electrodes are in antiphase. Due to capacitive coupling between the two strips they add with correct sign, thus providing the maximum possible output power.

The number of fingers on the interdigital transducers is lower the higher the intended bandwidth. Their aperture is about 30 wavelengths. Multistrip beam compressors consisting of a large number of almost parallel metal strips are located between the transducers and the waveguides. These strips are slightly curved in a particular way in accordance with complex computer programs so that the potential tapped off on the sides of the wide incident wave cause a concentrated wave to be excited in the center. **Fig. 7** shows a scanning electron micrograph of the waves in the beam compressor. In calculating this strip pattern, diffraction effects have already been taken into account so that the resultant beam profile corresponds precisely to the mode profile of the waveguide and, therefore, practically no coupling losses occur [5].

In the design shown in **Fig. 5** the layer thickness of the waveguide metallization must be selected to produce a minimum in the dispersion over the desired bandwidth. The thin layer resulting from this requirement is unfavorable for the interdigital transducers, as it would make the ohmic losses in the fingers excessively high. For this reason, transducers and waveguides must be fabricated with different layer thicknesses in two photolithographic steps. This is unusual and undesirable in SAW device technology. Consequently, an alternative approach has recently been developed [6] which combines a number of advantages. Instead of the transducers shown in **Fig. 5** with few fingers and a large aperture, it is also possible to use small-aperture transducers with a larger number of fingers in order to obtain the impedance required for matching. In order to ensure that these transducers acquire the desired bandwidth, the fingers are spaced along the transducer with increasing or decreasing periodicity, so that only some of the fingers are effective at each frequency.

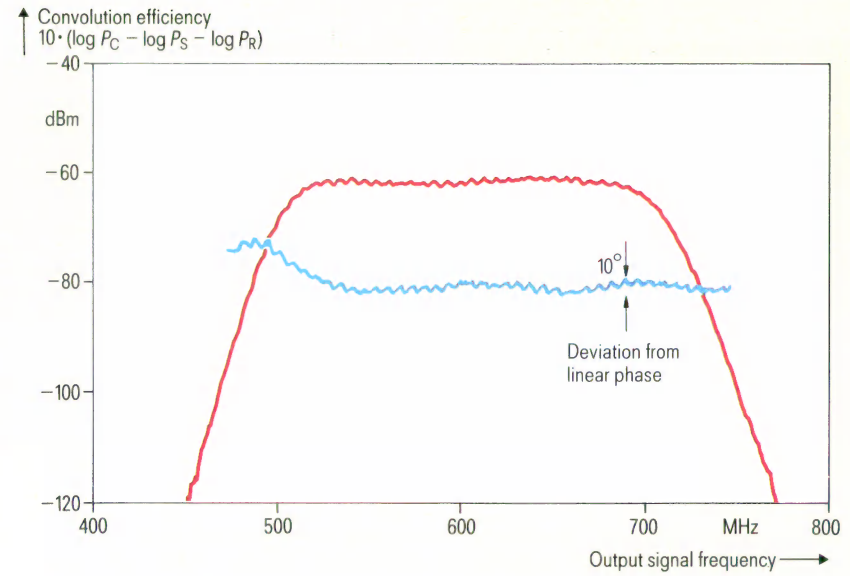

Fig. 9 Measured efficiency of convolver with 95-MHz bandwidth (referred to the input signals). The red curve represents the magnitude of the efficiency; the blue curve represents the phase, showing excellent phase linearity

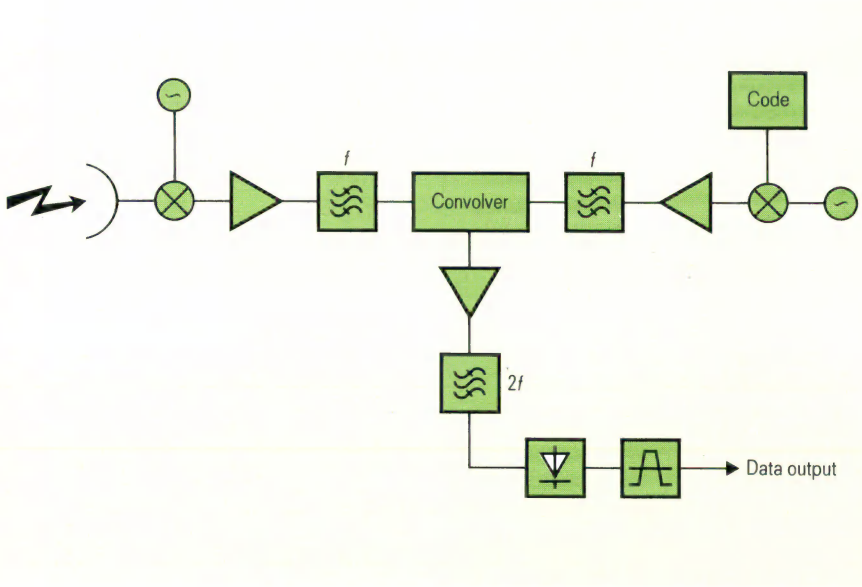

Fig. 10 Basic principle of a receiver for spread spectrum signals with convolver-based correlator

The undesirable dispersivity of these transducers (various frequencies are produced at different distances from the waveguide) is compensated by using transducers with opposite dispersion at both ends of the convolver. In addition, the dispersion of these transducers can be adjusted so as to compensate for the dispersion of the waveguide and matching network. This removes the constraints on selecting waveguide layer thickness so that the entire convolver structure can be fabricated in one photolithographic step using a single metallization. As this interdigital transducer already has a very small aperture, a beam compressor is superfluous. However, diffraction effects occur even in the transducer. These can be counteracted by slightly curving the trans-

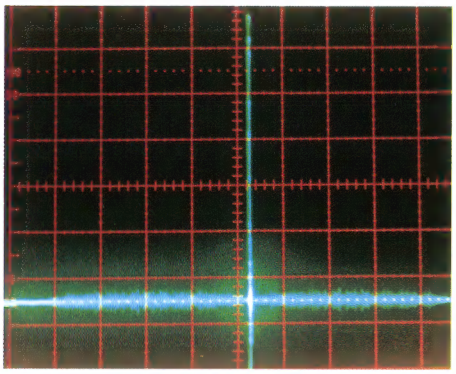

Fig. 11 Convolver output signal: autocorrelation function of 1023-bit code with 75-MHz clock frequency (timescale ≙ 1.3 µs per division)

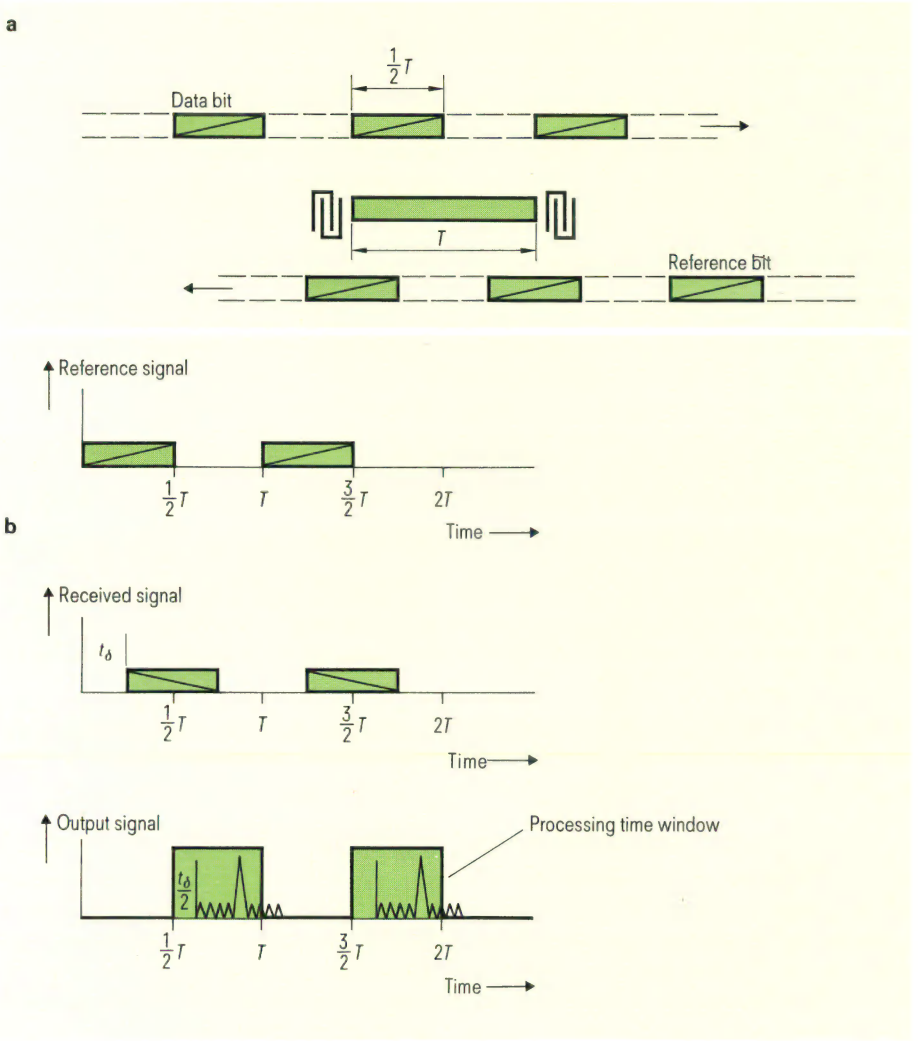

Fig. 12 Signal timing diagram in a receiver as illustrated in *Fig. 10* without synchronization. With synchronization, a 100% duty cycle can be achieved in the signal. Part a depicts the temporal and spatial relationship of the two signals entering the convolver; part b depicts the relative timing of the input and output signals

ducer fingers so that the waves are focused on the end of the waveguide (**Fig. 8**). In addition, the aperture of the active finger overlaps must be shaped so as to provide optimum overlapping between the diffraction profile of the waveguide mode and the exciting transducer at any distance from the end of the waveguide. This produces the clariform shape of the active region of the transducer, as shown in **Fig. 8**. Using a suitable method of optimizing the dispersion characteristic of the transducers, it is possible to shape the amplitude and phase of the efficiency as required.

Fig. 9 shows the measured efficiency of a convolver with a bandwidth of 95 MHz, referred to the input signals. In this case the deviation from linear phase is no more than ± 5°.

Possible convolver applications

Fig. 10 shows the basic principle of a receiver for spread spectrum signals with a convolver. The received signal is converted to the center frequency of the convolver, while the code generator produces a time-reversed version of the code contained in the signal to be received. This version is fed to the convolver's reference signal input. When the expected signal arrives in the convolver, it overlaps the reference signal and, if the two signals are identical, the autocorrelation function of the code is obtained as the convolver output signal (**Fig. 11**). Complete overlapping of the signal and reference inside the convolver requires coarse synchronization which can be readily established within a few code cycles with only approximate coincidence. However, if the signal is not longer than half the processing time inside the convolver and the reference is applied cyclically, complete overlapping within the convolver is ensured without further synchronization. If, however, the signal sequence is uninterrupted, it is necessary to take account of multiple correlations. These occur when a signal segment is convolved not only with the relevant reference segment with which it fully overlaps in the convolver, but also with the preceding or following reference signal segment on entering or leaving the convolver, thereby forming a spurious correlation (**Fig. 12**). These partial correlations can be gated out. Due to the time compression factor of 2, no information is lost in the process.

Cost-effective fabrication of SAW components is currently restricted to three-inch wafers. This limits the realizable convolver intergration time to a maximum of 18 µs, although convolvers with 45 µs integration times on specially cut single substrates have already been demonstrated. The maximum practical bandwidth results from the fact that above a relative bandwidth of about 25% of the center frequency, any increase in interdigital transducer bandwidth must be traded against increased insertion loss. However, if the center frequency is raised, the acoustic attenuation on the waveguide increases quadratically. A bandwidth of 160 MHz at a maximum efficiency of −63 dBm has already been achieved in the Siemens Corporate Research Laboratory.

The top end of the dynamic range provided by the convolver is determined by the maximum input power of some 25 to

30 dBm which the transducers can handle, and the bottom end by the thermal noise or the intrinsic noise level due to autocorrelation of the reference signal. The filters preceding and following the convolver in **Fig. 10** are used to shield the output signal, which is double the frequency of the input signals, against direct feedthrough (crosstalk) from the input. Maximizing the feedthrough suppression of the convolver itself helps to minimize filtering requirements. Approximately 100 dB of feedthrough suppression can be obtained with suitable shielding inside the device.

With a time-bandwidth product of 2500 and a dynamic range of 48 dB, a SAW convolver performs $2.5 \cdot 10^{11}$ 8 · 1 bit multiplications per second. This performance is still orders of magnitude higher than the processing speed currently achievable using individual digital signal processor chips.

The Federal Communications Commission (FCC) in the USA has authorized the rather free use of spread spectrum systems in frequency bands allocated for public safety service applications, for industrial, scientific and medical uses, and for amateur radio application [7]. This development demonstrates that there is an interesting future in store for spread spectrum systems and for the application of SAW convolvers in these systems.

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Dietmar Gernegross and Klaus-Dieter Kahn

Designing Semi-Custom Integrated Circuits

The use of semi-custom integrated circuits in digital radio relay transmission equipment offers considerable advantages, such as compactness, lower power dissipation and higher reliability. As a result of these improved characteristics, it has been possible to develop equipment which could not have been implemented using standard circuits – e.g. low power designs, equipment with complex signal processing functions or large transmission capacities. The anticipated production volumes and the complexity of the kind of ICs used for transmission equipment are at an economic optimum above standard and below full-custom parts. Their technical and economic significance is constantly growing.

Semi-custom integrated circuits

Semi-custom integrated circuits are devices which are prefabricated by the semiconductor manufacturer and then finished to suit the customer's requirements. This distinguishes them from standard circuits on the one hand and full-custom circuits on the other.

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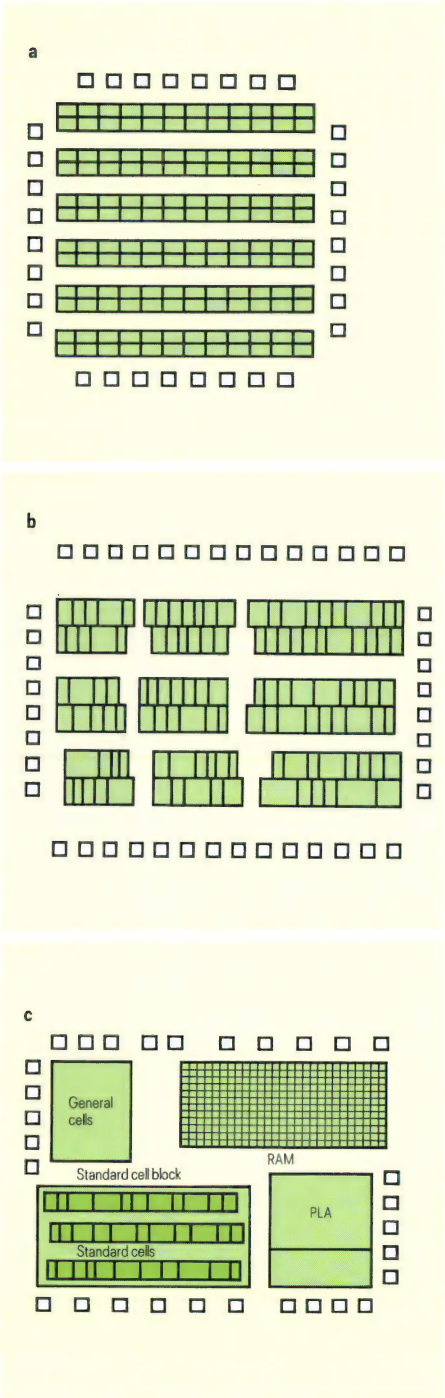
With cell-based integrated circuit design a distinction must be drawn between standard cells with certain "standardized" dimensions and locations and general cells which can be placed in any position specified by the customer. In a gate array, fixed locations are provided for the cells (**Figs. 1** and **2**). The cells are mostly functional blocks (macros) available from a semiconductor manufacturer's cell library.

In many cases, it is also possible to design new cells tailored to a customer's needs. The specification for the new cells to be designed then includes the cell interconnections as well as the content and placement of the individual cells.

The semiconductor manufacturers provide comprehensive aids and programs for developing and fabricating an integrated circuit. With appropriate software, these programs can often be made to run on a variety of workstations. The technology in which the integrated circuit is designed determines the processing speed (clock frequency) and the packaging density – the products offered range from very small (< 100 transistors) to very large units.

Circuit design for digital radio relay systems

Before designing new equipment it is essential to know the characteristics of the technologies available. For transmission speeds up to 34 Mbit/s, CMOS (complementary metal oxide semiconductor) technology is used (gate arrays, standard cells and general cells). For bit rates of 140 Mbit/s and over, ECL (emitter coupled logic) in bipolar technology is used (gate arrays, transistor arrays, standard cells).



PLA Programmable logic array
RAM Random access memory

Fig. 1 Cell structures for integrated circuits

a Gate array
b Standard cell
c General cell

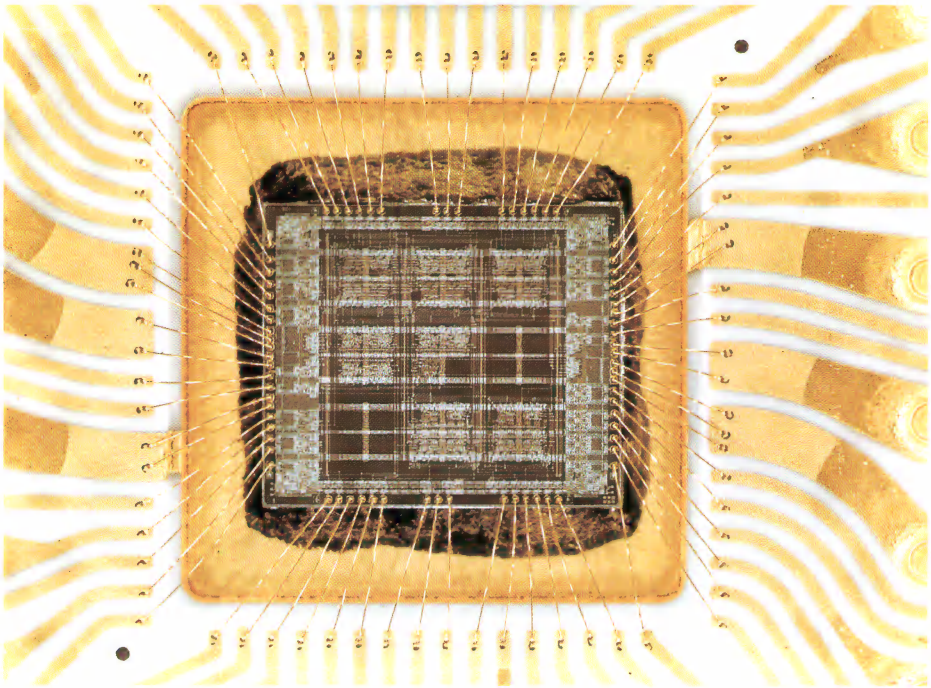


Fig. 2 ECL gate array with package open

When a technology is being optimally utilized, it is the design of the functional blocks (macros) of a chip family that often decides how it can be used. With highly complex digital signal processing, the aim at higher bit rates is to provide parallel processing in order to utilize the higher packaging density and lower power consumption of CMOS technology. General cells or an optimized, full-custom design are mainly used in such applications.

By implementing as many equipment functions as possible in a small number of circuits, power consumption and space requirement are minimized. As the non-integratable functions are mainly "analog," the ability of a circuit family to interface with its environment is very important. Further circuit selection criteria are the temperature range (outdoor, air-conditioned or non-air-conditioned rooms), the desired reliability and the anticipated production volume. Integrated circuits are used, for instance, in digital radio relay equipment for digital signal processing in the baseband [1, 2], as a regenerator device for carrier and timing recovery [1], as an amplifier and double-balanced modulator and as part of an adaptive equalizer [3].

Specification of integratable circuit sections

When the functions of a system have been distributed among individual equipments, the integratable circuit sections are specified and the inputs and outputs defined. Since the aim is for as many signal processing operations as possible to be performed by large-scale integrated circuits, analog functions often occur at the interfaces to the environment. If a complex function has to be distributed among several devices, the interfaces must be specified for each chip. This provides the opportunity to design multi-purpose chips, e.g. an identical central clock unit for transmitter and receiver [1] – thus reducing the development effort and increasing the production volume. When specifying the interfaces, it must be remembered that considerable computer time is required to test large complex functions during subsequent chip simulation, that analog functions are difficult to incorporate in the (digital) simulations and that as many of the expected equipment operation states as possible must be taken into account.

Functional design of a semi-custom integrated circuit

Functional design of an integrated circuit is performed with the aid of a Siemens software system (VENUS) for the development of very large scale integrated (VLSI) chips [4, 5]. This cell-based design system for digital semi-custom integrated circuits has been developed by the Corporate Technology Division of Siemens AG.

Circuit design starts with the formation of subfunctions which can be developed and tested independently of one another as far as possible. Consideration must be given even at this stage to subsequent device testability.

Using the cell catalog of the semiconductor manufacturer (at Siemens generally the Components Group Integrated Circuits Plant), the first step is to specify the complex central functions such as the clock supply and then to implement the individual functions with internal connections or external inputs and outputs.

Compliance with VENUS design rules is essential for trouble-free execution.

Fig. 3 Workstation for graphical input of the circuit diagram of a designed integrated circuit

Circuit diagram generation

The diagram of a designed circuit is entered graphically on a workstation (alphanumeric and graphic terminal, **Fig. 3**). At the start of this stage it is necessary to select the appropriate library depending on the type of circuit required (ECL or CMOS, gate array or standard cells). When the circuit diagram has been entered, the program runs a formal check on the circuit diagram, reporting any unconnected circuit element inputs. If the check reveals errors, the circuit diagram must be corrected and then rechecked. The circuit diagram is printed out on a plotter connected to the workstation.

Logic verification

Circuit diagram entry is followed by logic simulation, for which a circuit model is automatically generated from the diagram. In addition, the development engineer must enter the bit patterns (stimuli) required for the simulation in the form of a list, from which the output signals are then calculated. A simulation run can be optionally executed for the "typical", "slow" or "fast" delay times. The results are presented both in tabular form and as a time diagram. Undefined conditions occurring during simulation are indicated by the program. If the simulation results are unsatisfactory, either the simulation bit patterns or the circuit diagram must be modified; logic simulation is then started again. The above sequence is repeated for all circuit sections and also for the circuit as a whole until the simulation yields the desired result.

In circuits with critical time delay paths, it is also possible to perform a simulation which takes account of the anticipated delay increases due to the inputs of the receiving cells, even before actually doing the layout. The data required for this purpose can be generated using VENUS.

Testability analysis

The testability analysis is used as the basis for test program generation. It provides information concerning *fault coverage* and therefore also the *testability* (test stringency) of a circuit. In order to determine the fault coverage, test bit patterns are required which can be generated from the bit patterns produced for logic simulation, or automatically using a stimulus generator. The output bit patterns obtained from the fault-free circuit in response to the test stimuli are established by a cycle simulation. These responses are used for comparison with the responses obtained in the subsequent fault simulation. The cycle simulation and a simulation with "built-in faults" are compared and the differences reveal the detectability of the faults.

It is from the fault simulation that the fault coverage is obtained. If the latter is too low despite compliance with test-engineering design rules, additional test stimuli must be generated either manually or automatically. It may even be necessary to modify the circuit, requiring a complete run through the sequence from logic simulation to fault simulation. If fault coverage is adequate, the test stimuli are evaluated and saved for subsequent test program generation.

Physical design of a semi-custom integrated circuit

Like the functional design, the physical design of a semi-custom integrated circuit is carried out using VENUS. The standards of the process technology are

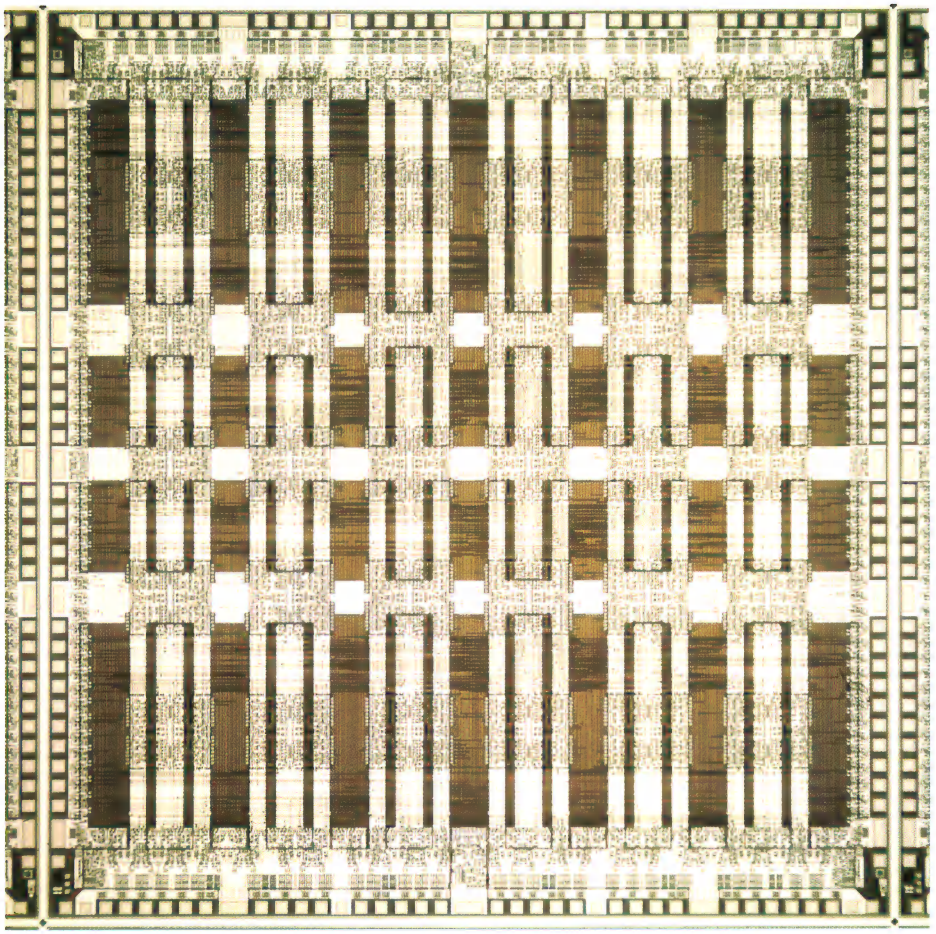


Fig. 4 Detail of the routing in an ECL gate array

automatically complied with by the design system.

Chip design

The chip design, which consists of placement and routing (layouting), is generated largely automatically. For this purpose, the programs require the circuit model entered during logic simulation, the system files with the logical and physical description of the cells and line factors as well as a control file, some of which must be entered manually by the development engineer. For gate arrays, the control file contains the description of the master selected and the geometric design rules. Placement and routing are executed in a closed-loop procedure with no possibility of interactive intervention. Manual rerouting can be executed afterwards on a graphic terminal. Placement and routing objectives must be stated when entering the circuit diagram.

For standard cells, the information entered in the control file includes such factors as the number of cells, the distribution of the edge cells and the signal weighting as well as the points in the program at which manual interventions are to be possible. With manual intervention, it is possible to optimize the chip area utilization (e.g. by relocating cells), the routing (e.g. by rotating and mirroring cells) and the dynamic response (e.g. by line weighting). As with gate arrays, it is also possible to reroute the layout of standard cells.

Fig. 4 shows a detail of the routing in an ECL gate array.

Delay analysis

For delay analysis, a logic simulation is performed taking into account the dynamic response of the conduction paths (cell output to cell input). The signal delay times are calculated taking into account the cell output impedance, the capacitive and resistive loading due to connection paths, as well as the input capacitances of the receiving cells. If the simulation result differs from that anticipated (compared with the simulation obtained from "functional design"), it is then necessary to modify the layout, stimulus or circuit diagram depending on the cause. According to the outcome, the relevant program steps must be repeated from that point onwards.

Fabrication data

The chip design results are converted with program assistance to produce the layout design and the magnetic tape for controlling mask fabrication. To do this, the user requires no knowledge of the fabrication process. Such items as framing elements (scribe lines, alignment and technology structures) and designation fields are entered automatically and the results logged. Another program is used to prepare a plotter control tape for recording all the layers used including those for mask control tape generation, and to prepare a bonding diagram.

Test program generation

The test program is generated automatically from the test stimuli produced during the testability analysis, from the circuit description and from a pin assignment file. The latter contains the assignment of the signal names to the test item pin numbers and to the channel numbers of the automatic tester. Both the chip on the wafer and the device (chip in package) are tested.

Prototype devices

The semiconductor manufacturer's first prototypes are tested using the test stimuli produced by the circuit development engineer. However, it is often advisable to investigate some of the device characteristics on a test adapter. It is then possible to use non-critical chips in the intended module immediately to test their interaction with other chips and to investigate the overall operation of the equipment. As equipment operation is extremely complex and must be trouble-free under different operating conditions, it may be necessary to subsequently modify the specifications and hence the functions. For an integrated circuit, this means a redesign, even though the chip satisfies the initial specification. This involves modifying the circuit diagram and rerunning the whole operation.

Documentation and backup

On completion of the development stage, the circuit data are concentrated onto a small number of files, backup files are created for subsequent access and the chip is documented.

Summary and prospects

Semi-custom integrated circuits are an ideal solution for signal processing tasks in digital transmission systems. They are therefore key elements in the realization of modern high-quality digital radio relay systems. Owing to their higher transmission capacity and improved frequency band utilization, future digital wideband radio relay systems require integrated circuits with higher processing speeds, greater complexity and lower power consumption. They therefore place more exacting demands on both the development system and the technology. The close cooperation between the Component Divisions Integrated Circuits Plant as the semiconductor manufacturer, the CAD Tool Development Department of the Corporate Technology Division and the Systems and Circuit Development Department provides a particularly sound basis for ensuring that these demands will be met.

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Wilhelm Wilhelm

Bipolar Technology for Semi-Custom ICs in High Data Rate Transmission Systems

The SH100B and SH100C are gate array families available for applications in digital transmission systems. The first category of these large-scale integrated circuits provides complexities ranging up to 900 gate functions with a gate delay of 0.5 ns, the second category up to 2500 gate functions with a gate delay of 0.35 ns. The maximum data rates are 250 and 350 Mbit/s, respectively. In order to improve the transmission characteristics, new cells for the SH100C family have been specially developed for high data rate operation. These cells employ the differential logic principle and are suitable for transmitting and processing data rates up to 700 Mbit/s.

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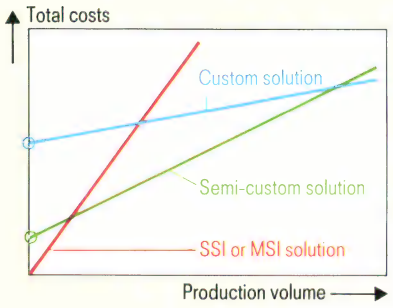
Both families employ oxide to provide electrical isolation between the components. The active elements are formed by implantation with a minimum structure width of 2 µm. Component interconnection is provided by multilayer techniques. Type series SH100B uses two metal layers with oxide for isolation, while series SH100C employs two or three metal layers with polyimide as the dielectric.

In the processing of high data rates there is a discernible trend towards large-scale integrated (LSI) circuits. There are several reasons for this:

- For complex logic functions it is easier to achieve a high switching speed with an LSI circuit than with a configuration of several circuits and few gates (SSI small-scale integration, MSI medium-scale integration). In the LSI implementation, the parasitic effects, which result from the interconnection lines and limit the switching times, are less significant and more easily controlled.
- For the same reason, the power dissipation per gate function is considerably lower in LSI devices than in smaller-scale integrated circuits.
- Total integration can be expected to provide considerably better reliability.

These arguments in favor of the large-scale integration of logic functions have to be weighed against the relatively low quantity of these devices required particularly in high data rate transmission systems.

The point is that the development costs of custom LSI circuits are not inconsiderable and have to be amortized from an ever-decreasing quantity of devices as the scale of integration increases.



MSI Medium scale integration
SSI Small scale integration

Fig. 1 Cost of integrated circuits for different system solutions

A solution to this problem is available in the form of semi-custom circuits whose development is largely automated and whose costs can be predicted and closely controlled (**Fig. 1**).

Gate arrays

Semi-custom circuits (gate arrays) are a particularly economical solution to the above problem. They employ prefabricated semiconductor devices (masters) on which suitable interconnections are deposited to implement desired logic circuits. The gate circuits (cells) employed have been tested and their electrical description and layout stored in a library. Placement and interconnection of the cells are largely automated. Suitable logic simulation programs check the

Number of gates	SH 100 B	SH 100 C
	Delay 0.5 ns	Delay 0.35 ns
700	24 cells	
700	24 cells + RAM	
900	36 cells	36 cells
2500		120 cells

Table 1 SH 100 B and SH 100 C gate array families

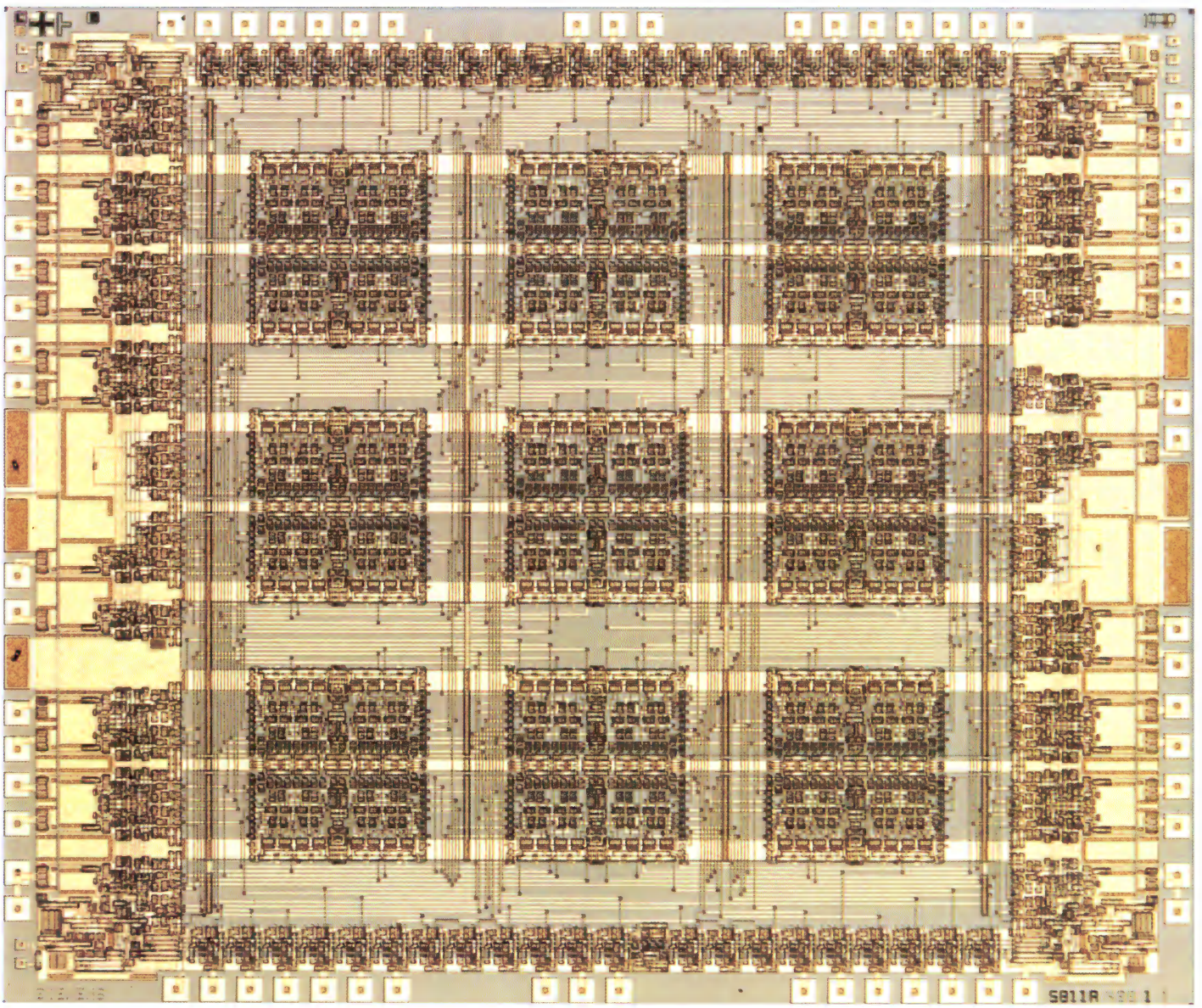


Fig. 2 SH 100 C bipolar gate array in emitter-coupled logic (ECL) technology with 36 cells (chip size: 36 mm²; complexity: 900 gate functions; gate delay: 0.5 ns)

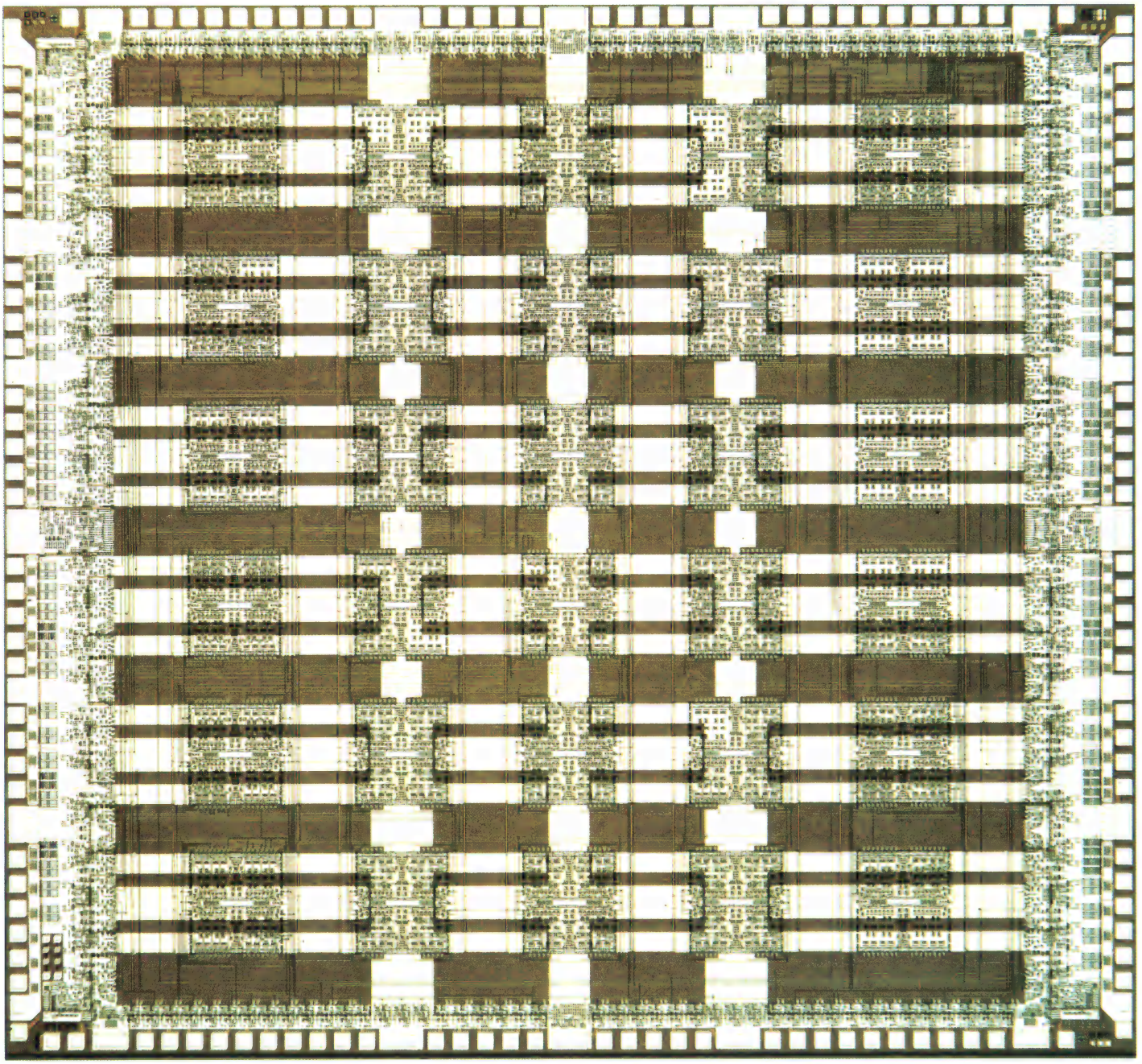


Fig. 3 SH100C3 bipolar gate array in emitter-coupled logic (ECL) technology with 120 cells (chip size: 75 mm^2; complexity: 2500 gate functions; gate delay: 0.35 ns)

overall functioning and form the basis for test programs. The use of gate arrays enables development costs to be kept to a minimum. The simulation programs and the high level of automation minimize the development risk so that a redesign is not usually necessary.

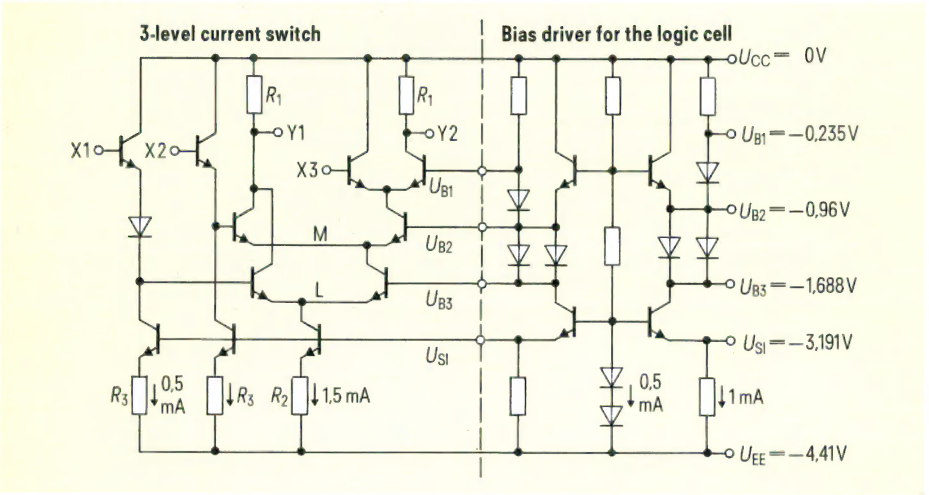
The fabrication of device variants is limited to producing interconnect levels, so that the time to produce the first functional models from the control tape is merely a matter of weeks.

Bipolar gate arrays

Types of master

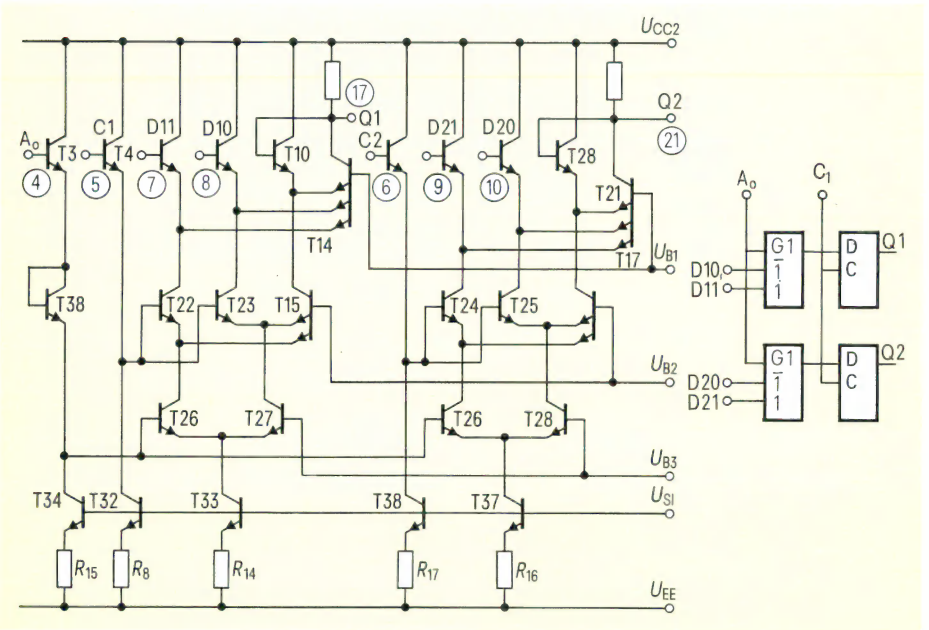
Special devices for processing high data rates (>100 Mbit/s) are integrated circuits employing a modern oxide-isolated bipolar technology. Siemens currently has five types of master available in this technology (**Table 1**). Three of these types belong to the SH100B family which has been in production since 1980 [1]. They feature a gate delay of 0.5 ns and a complexity of between 760 gate functions for the 24 cell device and 900 gate functions for the 36 cell type (**Fig. 2**). In addition, there is a master incorporating 24 logic cells and a 128-bit random access memory (RAM). For digital radio relay units, a series of SH100B devices has been developed and employed for transmitting 140-Mbit/s signals [2, 3].

The second and more modern SH100C family has two members, i.e. one master with 36 cells and one with 120 cells on which up to 2500 gate functions can be



U_B Bias voltage
U_{CC} Positive supply potential
U_{EE} Negative supply potential
U_{SI} Current source potential
X Signal input
Y Signal output

Fig. 4 Basic circuit of a cell with bias driver



A Address for multiplexer
C Clock input
D Data input
G Multiplexer input
Q Signal output
U_B Bias voltage
U_{CC} Positive supply potential
U_{EE} Negative supply potential
U_{SI} Current source potential

Fig. 5 Integrated circuit using three potential levels (double D latch with input multiplexer)

realized [2]. The typical gate delay for the SH100C family shown in **Fig. 3** is 0.35 ns.

Cell library

The cell library provides some 100 different circuits which can be positioned on any cell location on the master. The main types are summarized in **Table 2**.

Cell type	*Functions per cell*
OR, NOR	4
2-bit multiplexer	4
4-bit multiplexer	2
Latch	4
Master-slave flipflop	2
Full adder with carry	1

Table 2 Main types of cell in the cell library

Several cells can be used to form macros. A typical macro might be an 8-bit adder comprising twelve cells and having an addition time of 3 ns.

Fig. 4 shows the basic circuit of these cells. This design is referred to as current mode logic (CML) in which three levels of series gating are employed to form complex logic circuits. An example of a circuit using three potential levels is shown in **Fig. 5**. This is a double D latch with input multiplexer.

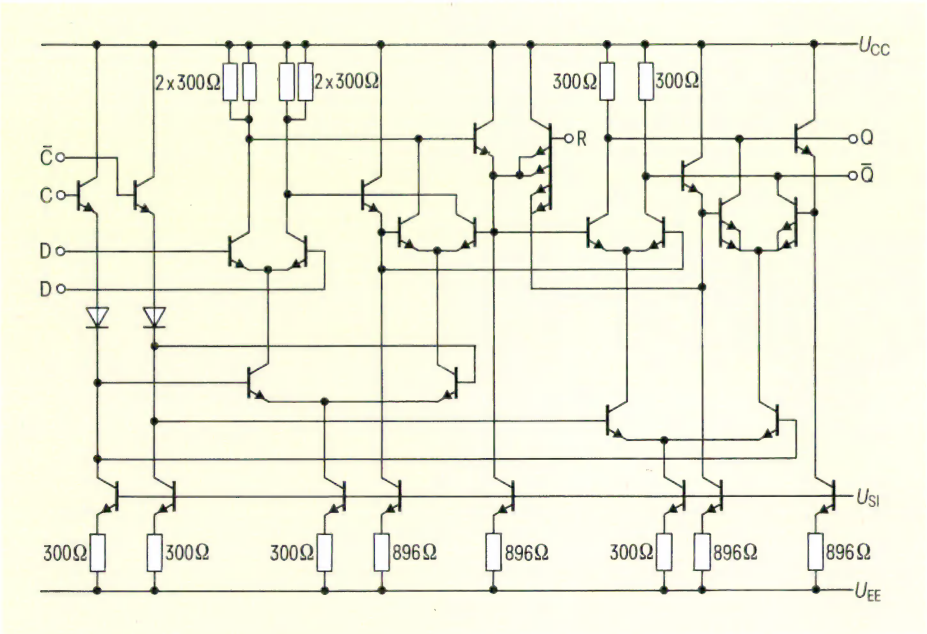
Converters are available for matching the external emitter coupled logic (ECL) level to the internal CML level with 450-mV signal swing. They are located at the edge of the chip and are also able to perform logic functions.

Special cells for high data rate signal processing

The cell circuits described are little suited for signals with a data rate in excess of 300 Mbit/s or for clock signals above 300 MHz. The reason for this is that their delays for positive and negative-going edges differ, so that short pulses passing through a chain of gates may sometimes be suppressed. These delay differences are due to parameter variations and nonlinear distortion. Circuits with differential logic [4], employing balanced signals, are unaffected by parameter variations and distortion on account of their carefully balanced design. They provide relatively stable performance into the 1-Gbit/s range [5].

The cell library has been expanded for this reason to include cells with differential logic. They are designed to be compatible with the other cell circuits. Examples are differential flipflops with and without input logic (**Fig. 6**). In addition, there are converters with differential logic to establish the connection to the outside world in a high-speed environment.

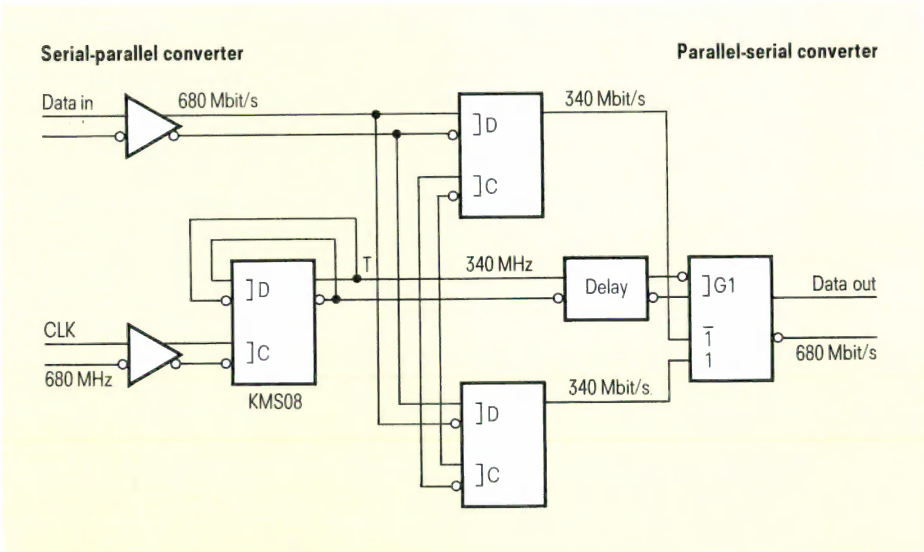
These cells can be used to make serial-parallel and parallel-serial converters up to 800 Mbit/s, enabling serial signals to be processed internally by ordinary single-ended cells at much reduced speed. The differential logic should preferably be restricted to certain areas of the overall circuit because it requires two lines per signal and is relatively complex for purely combinational logic.



C Clock input
D Data input
Q Signal output
R Reset input

U_{CC} Positive supply potential
U_{EE} Negative supply potential
U_{SI} Current source potential

Fig. 6 Basis circuit of a master-slave D flipflop with differential signals



C Clock input
CLK Clock signal

D Data input
G Multiplexer input

Fig. 7 Functional circuit diagram of a serial-parallel converter (left) and parallel-serial converter (right)

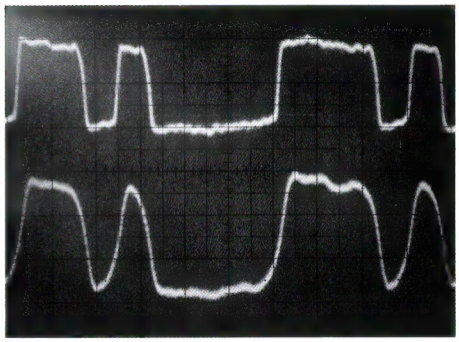


Fig. 8 Oscillograms of the input signals (DATA IN; below) and output signals (DATA OUT; above) of the parallel-serial converter at 680 Mbit/s

Typical circuits for serial-parallel and parallel-serial converters

The functional circuit diagram for these converters is reproduced in **Fig. 7**. For simplification, it merely shows an example in which the serial signal is converted to two half-speed data streams and vice versa. The two circuits have been tested and operate satisfactorily up to 1 Gbit/s. **Fig. 8** shows the oscillograms of the input and output signals for the parallel-serial converter at 680 Mbit/s.

Prospects

The development of gate arrays will not end at the first two families. Other families with higher speed and complexity will follow. A third generation with 9000 gate functions and 200 ps gate delay is currently under development. Less complex devices of similar speed, or optionally with a larger delay and lower power dissipation, are in the planning stage.

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CAUTION
HAZARDOUS
VOLTAGE
AND
RF FIELDS

Karlheinz Gosslau and Jürgen Wallner

Systematic Quality Assurance

Siemens develops, manufactures, markets and sells a wide range of high-quality products – from microelectronic components to large systems together with the associated software and services. As quality is a vital factor in Siemens' business policy, all the functional areas are actively involved in the important task of quality assurance. Supported by an effective quality assurance system, the Planning, Sales and Marketing, Development, Production, Installation and Customer Service departments work closely together to ensure that Siemens' products and services achieve the desired quality. The quality assurance organizations of Siemens' individual Groups, regional offices and companies abroad are coordinated to provide smooth interaction even across divisional boundaries.

The high level of quality required of communication products – and these requirements are becoming ever more exacting – means that problem elimination cannot be left until a unit or system has been deployed in the field. Good quality must be incorporated systematically in the product from its conception right through the planning, design and development stages. Quality must be a guiding principle in production and be borne constantly in mind through the shipping, installation, commissioning and maintenance stages. In short, throughout the entire lifetime of a product or system, all work must be informed by the maxim "Good work guarantees quality and creates satisfied customers".

Product quality – a Siemens' policy objective

"Good work, satisfied customers, new contracts" – this is the keynote of one of Siemens' numerous campaigns designed to ensure that all employees make the customer the focus of their thoughts and actions. For it is the customer who ultimately decides whether Siemens' overall performance – the products or systems as well as punctuality, installation, maintenance and cost-effectiveness – conform to his ideas of quality (**table**). As quality is not a fixed, measurable quantity, it is accordingly defined as the extent to which a product or service satisfies the customer's requirements [1].

Different requirements placed on a product call for different quality levels – nobody expects a "throw-away product" to have the same extremely high quality characteristics as, for example, telecommunication and security systems, i.e. systems and equipments which must operate reliably for 15 years or more in the field. Inadequate quality leads to high in-service maintenance costs, increasing expenses for both network operators and contractors. Conversely, quality in excess of what is required or reasonable is often unappreciated [2]. It is therefore imperative to identify as accurately as possible all the service and quality characteristics the market expects.

However, this information on which a new development is based does not remain constant. It changes during the planning, development and production engineering stages as the technology advances, and also as the customer's requirements change. At Siemens, such problems affect products from the entire field of electrical engineering with a wide range of equipments, systems and services to meet the extremely varied requirements. Having supplied this broad product spectrum for decades, Siemens have acquired extensive know-how and experience as well as a strong market position. A company with an

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Quality Audit in the
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Munich

Scheduling quality	*Technical quality*	*Economic quality*
Flexibility	Climate/EMC	Operating costs
Spares	Design	Customer price
Shipping	MTBF and MTTR	Life cycle cost
Installation	Standards and regulations	Consequential costs
Planning	Process control	Product costs
Deadlines	Reliability	Appreciability

EMC Electromagnetic compatibility
MTBF Mean time between failures
MTTR Mean time to repair

Table Quality has many aspects (listed above in alphabetical order under each heading) – each of these aspects may be important for the customer and the decisive factor in meeting his needs

◁ Base station for the C450 mobile radio system undergoing electromagnetic compatibility (EMC) testing

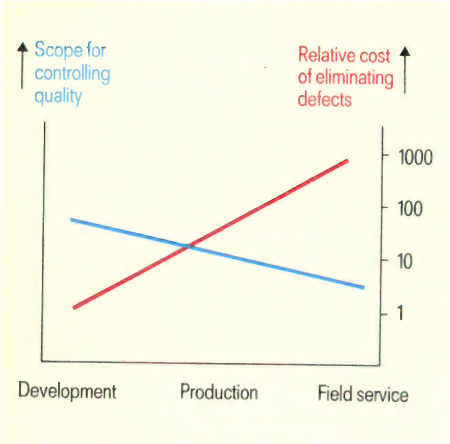


Fig. 1 Scope for and relative cost of eliminating product quality defects during development, production and field service

established reputation for high quality standards will readily be entrusted to meet these and all other standards both now and in the future.

Communication engineering demands the highest quality

The Telecommunication Networks and Security Systems Group is engaged in areas whose products and systems are subject to extremely high quality standards as exacting as the state of the art allows.

For example, customers demand system availabilities in excess of 99.95% for digital exchanges, i.e. less than four hours out of an entire year are set aside for repairs! In the case of bidirectional regenerators on transmission routes, customers demand trouble-free operation for up to 400 years MTBF (mean time between failures) which in statistical terms is only one failure in 400 years.

With requirements as demanding as these, quality may no longer be regarded as "secondary" and success left more or less to chance. Nor is it enough merely to specify measurements for the final inspection and then weed out defective parts in the test department. For it has long been recognized – even since the days when products still consisted "only" of hardware – that quality cannot be "tested into" a product. Now that products are evolving into systems comprising hardware, firmware and software which is finding increasing application even in transmission systems [3], any attempt to do so would be doomed to failure.

As it is very costly or – in the case of satellites – virtually impossible to rectify design or development errors subsequently, e.g. in the field (**Fig. 1**), it is essential to use only high-grade, qualified components [4]. Moreover, the basic principles of quality assurance must be applied right from the outset, and this is equally applicable to both hardware and software development. The slightest analytical error at this stage may have serious consequences and can prove extremely costly once systems are in service in the field.

With the numerous quality requirements becoming ever more stringent and complex and inevitably undergoing modification and addition throughout the course of planning, development and manufacture [5], it is beyond the scope of any one individual to follow their progress and verify that they are being met. This calls for teamwork involving the workforce as a whole and requires a carefully thought-out system of procedures.

High quality requires a systematic approach

Quality must be achieved *systematically* in all work phases and across all functional areas, i.e. quality assurance must be planned and systematized. At every stage of product development the requirements must be specified, the changes documented, their repercussions investigated and the responsibilities assigned.

A comprehensive system for this purpose has been established in a set of practices and precepts. This system controls the activities and interaction of the planning, development, sales and marketing, production, commercial, installation and maintenance functions in the area of quality assurance and is applicable to both hardware and software (**Fig. 2**). Moreover, it is also incorporated into the quality assurance functions of the sales and marketing organizations at home and abroad both in this and other Groups within Siemens AG.

The basic element of these practices and precepts is the *Quality Policy* of the Telecommunication Networks and Security Systems Group. It forms the framework within which

- the responsibility of the areas involved is defined according to the quality requirements;
- quality assurance is planned, implemented, monitored and documented

Fig. 2 Examples from the quality assurance (QA) Practices and Precepts of Telecommunication Networks and Security Systems

with the aid of coordinated documentation;

- the relevant standards as well as legal, contractual and other requirements are complied with;
- a continuous record can be provided as evidence of quality assurance and the responsibility for quality.

The Quality Policy is supplemented in depth by the *Quality Assurance Manual* which is organized in modular sections applicable to the entire Group with additional modules relating to the individual Divisions and functional areas. This manual describes the quality assurance system from planning and documentation through all the processes and testing procedures to installation, commissioning and quality reporting.

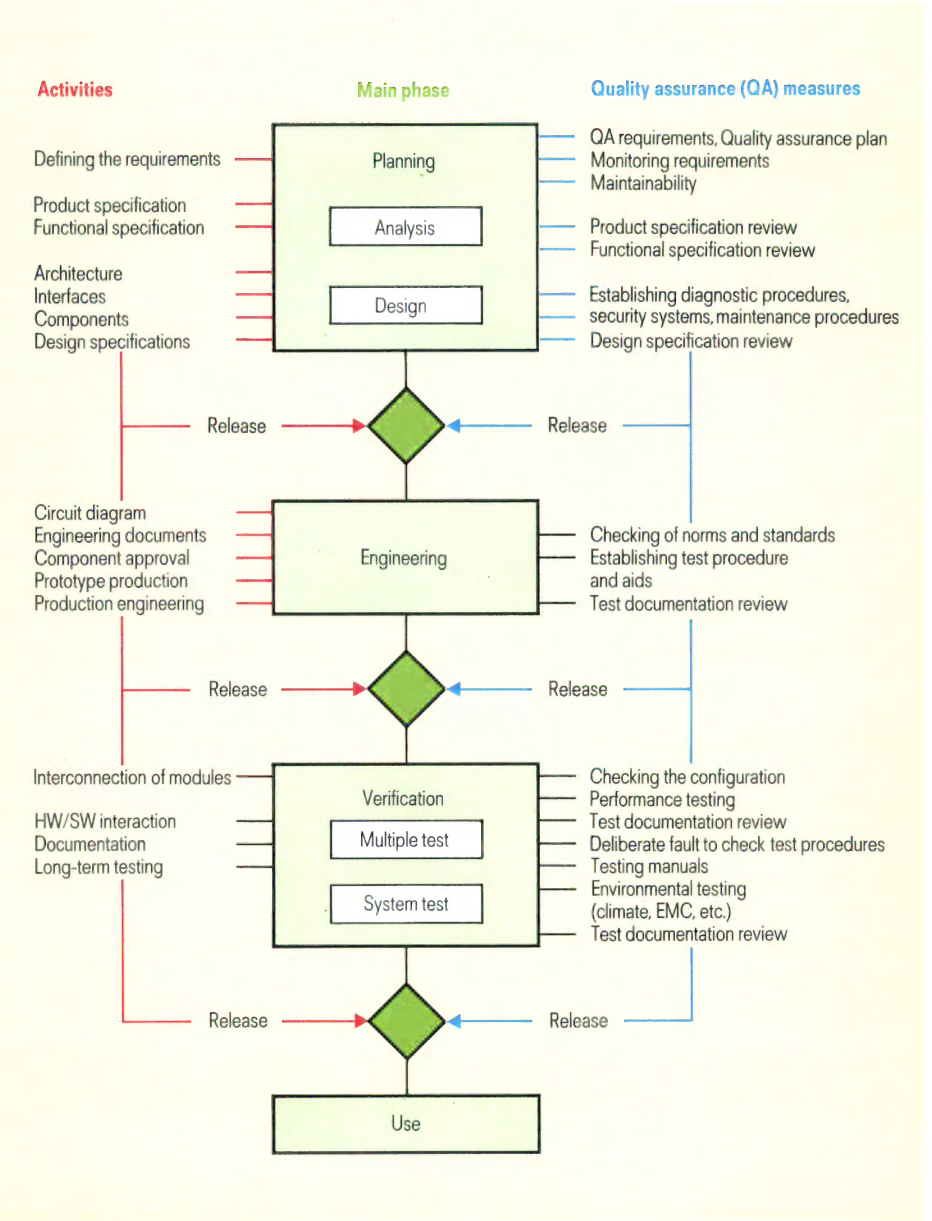
To give an example, all the development projects are broken down into phases. The three main phases are:

- planning (analysis and design),
- implementation (engineering), and
- verification (multiple and system testing).

In each of these phases, quality assurance procedures are prescribed in order to compare the results with the objectives specified in the development plan (**Fig. 3**).

The *Quality Assurance Plan* establishes final quality assurance procedures and responsibilities for specific products.

The Divisions have their own internal guidelines to supplement the Group practices and precepts, e.g. the "Quality Assurance Procedures for Development in the Transmission System Division". Other guidelines contain quality parameters for hardware and software development as well as instructions for carrying out quality audits.



EMC Electromagnetic compatibility
HW Hardware
SW Software

Fig. 3 Phase model for a development project with quality assurance procedures as specified in the Quality Assurance (QA) Manual

Good work from all involved – an essential requirement for high quality

The "secret" of high quality is, however, more than merely experience, knowledge and the resultant skill allied to elaborate quality assurance instructions. Just as inspecting the finished product only at the end of the manufacturing process on a pass-or-fail basis is no longer acceptable, it is now no longer considered adequate merely to check workmanship, i.e. employee performance. The aim is rather to motivate all employees to think in terms of high-quality work and to promote a total quality approach crossing functional boundaries.

A possible stumbling block to this approach is misguided profit center thinking. An example of this is the natural temptation to leave it to the next functional unit to eliminate detected weaknesses in order to save time and costs in one's own area. Since the costs of rectifying a defect increase logarithmically as the product progresses through the system, it must be realized that thinking on the lines of, "the people in the testing department will do that," or "our Customer Service staff will take care of that," is misguided and should therefore be rejected. Another problem is that this way of thinking and acting is not amenable to any form of checking. In clear recognition of these circumstances, Carl Friedrich von Siemens said as far back as 1935: "Quality is based on skill and skill on experience and education."

Ways of achieving quality work

Keeping the workforce constantly informed and providing systematic training in pursuance of these objectives are therefore an important aspect of Siemens' quality assurance system.

A number of basic and continuation seminars are regularly organized or jointly arranged by the Telecommunication Networks and Security Systems Group. Examples from the last three years include software management seminars, research and development seminars, and "Quality and Reliability of Communication Products" seminars. In these seminars, several hundred Group employees have been familiarized with the problems of quality [7]. Pamphlets such as "Controlling Quality" and "Quality Reporting" are issued to management personnel engaged in sales and marketing, development, and production in order to reinforce and update the content of the seminars.

These measures naturally involve considerable expense. However, in view of the constantly increasing complexity of technology, they are the only practicable way of achieving products and work of the high quality required.

Quality representatives are appointed in the divisions and functional areas to pursue these objectives and assist in defining product-related quality characteristics and qualifying procedures. They are assigned to the managers of the particular areas and assist them in their quality assurance functions. These quality representatives advise departments within their organizational unit in quality matters and verify that the quality assurance methods and procedures are implemented and effective. They have technical authority for implementing necessary improvements and cooperate with other quality representatives in coordinating quality assurance activities across divisional boundaries.

Another important task of the quality representatives is to cooperate closely with the central *Quality Audit* department (**Fig. 4**). The latter reports directly to the group management and is mainly responsible for

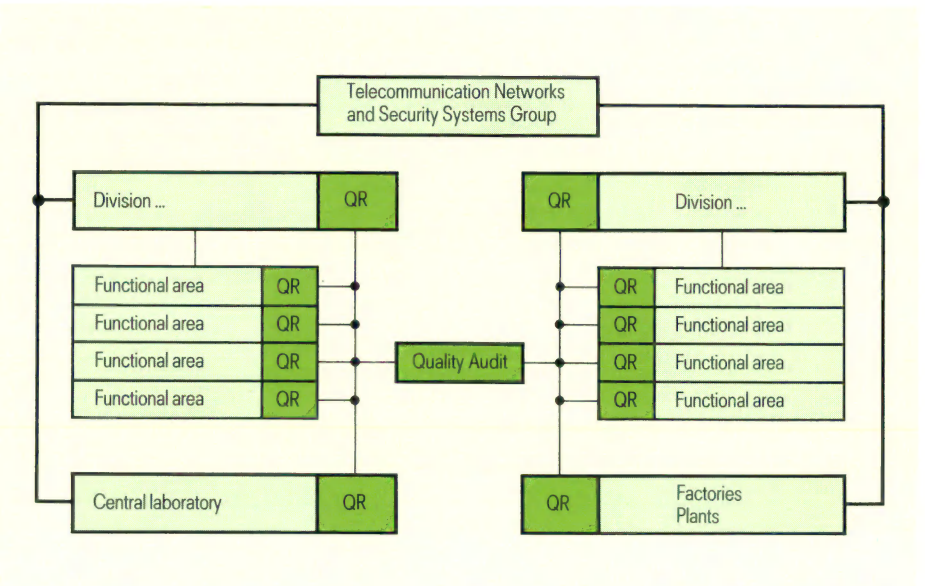
- *preparing quality assurance guidelines,*
- *advising the areas* on setting up their quality assurance systems and monitoring (auditing) the effectiveness of these systems,
- selective on-the-spot *quality audits and reviews.*

Quality audits are performed at unspecified times – mainly for a particular reason – but also in connection with major development projects where the particular management of the division or functional area wishes to monitor the progress of the project through the agency of a neutral body. The aims of these audits are to detect weaknesses and indicate possible improvements. Since no product or service can be so perfect as to be beyond improvement, recommendations arising from quality audits are made in order that the day-to-day operations of the functional areas may benefit from the wide-ranging, interdivisional experience of the central Quality Audit department in all the latest aspects of international quality assurance. Re-audits verify that the recommendations have been implemented and are effective.

In order to maintain the high standard achieved, the functional areas themselves perform internal quality audits to obtain continuous verification that their quality assurance systems and procedures are effective and also to provide evidence of this for their customers.

Unlike the audits by the central Quality Audit department which are selective and, as in most major companies, generally restricted to key areas and sampling, these internal audits are performed to a regular schedule. As each unit affected is informed in good time about the planned audit or re-audit, the employees concerned are naturally prompted to act on their own initiative in bringing their quality assurance procedures up to date. Experience shows that the employees are themselves extremely interested in finding possible improvements and introduce them into their daily work.

These efforts, too, must be systematically supported and encouraged. An effective approach is to set up quality circles – for example, Telecommunication Networks and Security Systems currently has some 120 quality circles [8]. Employees in these circles have already come up with over 300 improvements which have resulted in direct quality improvements. Continuation seminars are held in order to ensure that all those involved with quality matters, having once been motivated, do not lose their motivation. In addition, there are frequent internal campaigns with leaflets and posters displayed in offices and workshops to emphasize the importance of quality for Siemens' reputation with its customers and its consequences for future development and job security.



QR Quality representative

Fig. 4 Quality representatives in the Divisions and functional areas act in cooperation with the Quality Audit department

It is worth remembering that although many elaborate procedures are required to provide the high quality demanded of complex products and systems, they in no way raise the cost to the customer [9], indeed they may cut the life cycle costs considerably. Supplying high-quality items while maintaining good long-term customer relations by delivering on time and adopting a flexible approach to customers' problems are only some of the main aspects of Siemens' business policy.

The goal of this policy is to achieve a high rating for quality and then to maintain it. Work and product quality must be an integral part of a total approach and consequently of strategic corporate planning [10]. An exemplary and comprehensive quality assurance system, continuously monitored for conformance, is one of the most important aids to implementing this approach.

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Product Quality and Quality Assurance Right from the Start

Communication equipment must meet very exacting quality requirements. This is achieved by quality assurance procedures accompanying each product through all phases of development, testing and manufacture to eventual use by the customer. The reliability requirements imposed on equipment operated in communication networks are the basis for a comprehensive product-related quality assurance concept.

Fundamentals of quality assurance

The concept of quality assurance embraces all the procedures, criteria and tests necessary for verification of product quality in the development and production phases. For this purpose, product-related objectives are laid down for the individual components, modules and system sections; careful component selection and qualification together with computer-aided failure-rate predictions accompanying the development process and standard reliability tests ensure that these objectives are met.

The components employed in transmission systems may be divided into two categories. One comprises standard items for routine use in large quantities, which are recorded in continuously updated lists of preferred components. The other category comprises special-purpose devices – e.g. microwave semiconductors – requiring additional quality assurance procedures and for which additional component-related quality plans must be drawn up to supplement the specifications for standard components.

The application of quality assurance even before the product is developed ensures its fitness for use under specified operating and environmental conditions. This involves tests covering all the measurable performance characteristics, laws, regulations and safety requirements.

Quality requirements

The availability required of the transmission networks and units for the particular application together with continuous market surveillance for components, modules and units provide the basis for establishing the environmental conditions and quality objectives of the new product in the product planning phase. Where possible and desirable, the requirements placed on a new equipment generation are derived from experience acquired with older equipment fulfilling a similar function.

The relevant environmental conditions for a worldwide application are always taken into account by selecting suitable climatograms, e.g. per IEC 721. National and international quality standards such as ISO and CCIR are also used. In parallel with the technical specifications, the quality requirements are also established in clear and mandatory form.

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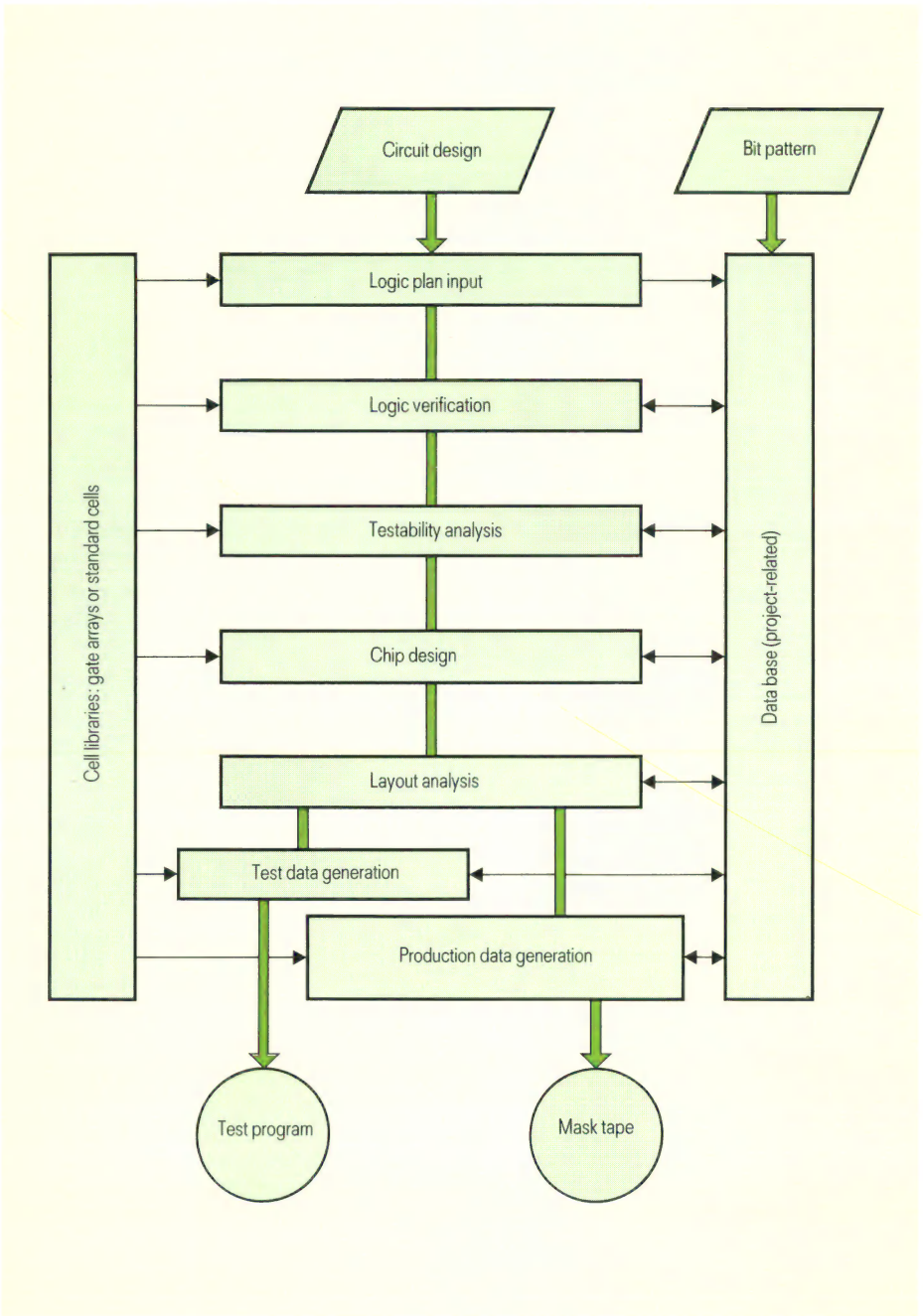


Fig. 1 Development steps in the VENUS design system

Establishing the quality concept

The technical feasibility of new equipment concepts and the scope for applying advanced technologies are examined in study projects during preliminary development. Quality assurance experts are involved even in this phase in order to ensure that sound quality data enter the product development process at an early stage. Experience with technically comparable equipment is helpful in establishing quality objectives particularly for the mean time between failure (MTBF) or the failure rates of modules, slide-in units and insets. These failure rates are compared with the values specified by customers. The target values for the individual module are closely related to the availability for transmission links of a certain type and length, for example, as defined by the CCIR. In this phase, consideration is also given to whether and where redundancy should be provided in a transmission system and how to assign redundancy to functional entities. Consideration is similarly given to size, volume and packing densities and any resulting temperature problems.

Development – the basis of quality

The quality concept described above compels the development engineer to apply the same care in meeting the quality requirements as the electrical specifications. He is assisted in this task by development rules for quality assurance laid down in the Company's internal guidelines. The department in charge of developing the product is responsible for preparing and collecting all the quality assurance documents specified in the guidelines and for filing them with the other documents. Similarly, all experience, knowledge and suggested improvements are concentrated at a central location.

One of these guidelines includes checklists, e.g. for component selection, staying within specified stress limits, burn-in requirements, testing, type of materials used and their susceptibility to corrosion. It also gives the development engineer recommendations on component derating and indicates the resultant gain in reliability. In addition, the development engineer must repeatedly carry out prediction calculations to determine the failure rates or MTBFs of his designs. In this way, he is able to detect and eliminate possible weaknesses in his design at an early stage. Other guidelines ensure such factors as testability, producibility and appropriate material selection.

Quality through modern circuit design

There is an increasing need for highly complex functional entities in engineering new types of radio systems. A vital requirement for ensuring that these entities are of consistently high quality is the use of hybrid [1] and monolithic integration technologies [2].

Typical examples of the widespread use of large-scale integrated digital circuits are control sections in mobile radio units [3] and digital radio modems (DRM 34/70 [4], DRM 140/140 [5]). Computer-aided design (CAD) is an invaluable tool in designing these complex devices. It determines both the quality of the resultant products (tolerance analyses, testability analyses, etc.) and the number of circuit modifications or redesigns required in the course of development (simulation reliability).

Such tools are indispensable, particularly for designing VLSI circuits (very large scale integration). An example of this is the VLSI design system, VENUS, whose application is described with the flowchart in **Fig. 1**. The circuits to be designed may be of the semi-custom type [2 and 7] – such as gate arrays and standard cell designs – or the full-custom type. The circuit diagram is built up via workstations with graphics input. On the basis of this circuit data, the initial simulations are run to verify basic conformance to the specification. In all subsequent steps of the development process (component location, wiring, etc.), the design system constantly checks to ensure conformance to the circuit diagram. Similarly, following chip design, simulation data (e.g. signal delays) are automatically extracted and used for verification. Running the functional and physical designs in parallel throughout enhances design reliability and reduces throughput times.

Integrated circuits are tested on special automatic machines. The test programs required for this purpose are automatically generated by VENUS both for functional testing with bit patterns and for parameter testing (level, leakage currents, etc.).

VENUS finally generates production data on the number and type of cells on the device and control tapes for mask production. In addition, the control tape contains data for checking the various stages of the production process.

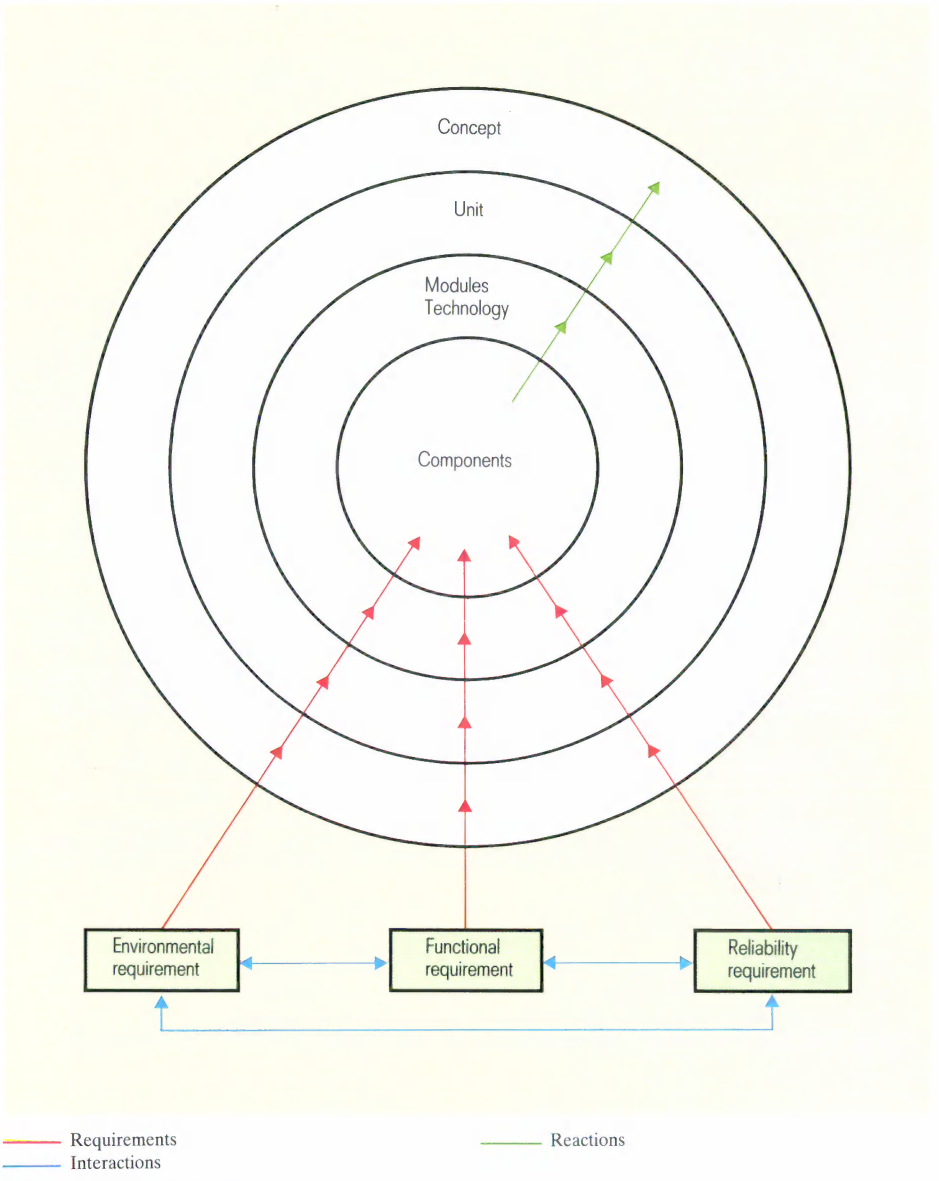


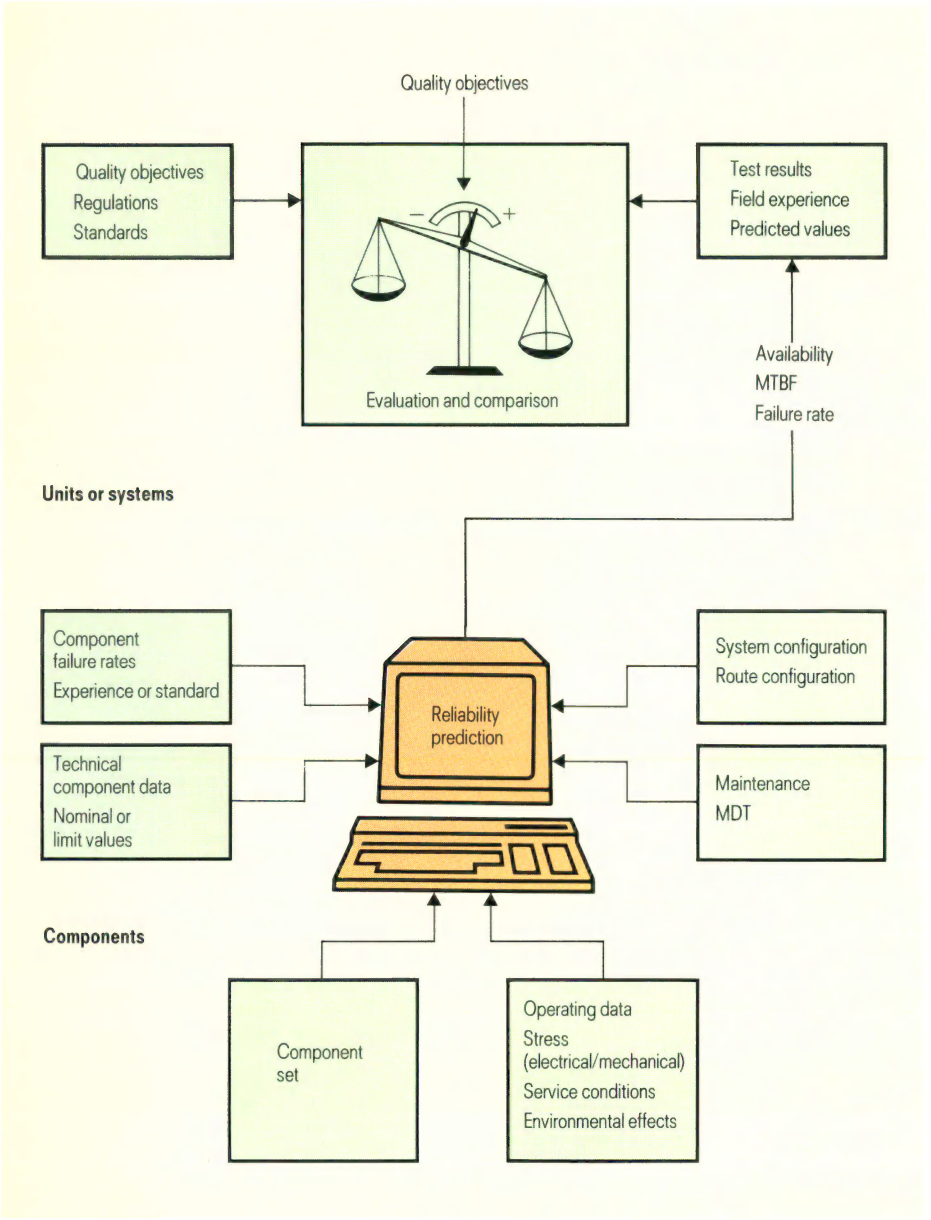
Fig. 2 **Quality interaction structure**

Computer-assisted reliability predictions

An essential part of the quality assurance concept is calculating predicted module failure rates. The results of these calculations, together with the quality objectives derived from standards and regulations as well as information obtained from test reports and from operating transmission equipment in the field, form the basis of the prediction system shown in **Fig. 2**. This system distinguishes between three basic variables: the functional requirements, the reliability requirements and the environmental requirements. Each technical condition is generally a compromise between these three types of requirement which have to be taken into account at every stage from defining the equipment concept through to selecting suitable and reliable components.

It is therefore crucially important to obtain a computer-based reliability prediction even before the module development stage. The heart of the prediction system is an interactive VDU workstation whose computer has access to a series of files (**Fig. 3**). The number and type of the components used in the module are stored in the "component set" file. The "component failure rate" file contains the basic failure rates of the components and the "technical component data" file provides the nominal and limit values at which they may be operated. These values, together with the operating data relating to the electrical and mechanical stress on the components and to the service and environmental conditions, provide the basis for calculating the failure rate or the MTBF of the modules and units. In order to calculate availability, additional data are required concerning the system and route structure, i.e. the configuration of equipment systems and transmission routes, and the mean down time (MDT). From information about the maintenance approach, the optimum number of replacement modules and components is derived by formulating the mathematical relationships accordingly.

These calculations are performed repeatedly during the design and devel-



MDT Mean down time MTBF Mean time between failures

Fig. 3 Computer-assisted analysis of technical data regarding components, systems, operating conditions and environment provides accurate reliability predictions at an early stage

opment phase for a unit and its component parts, e.g. in order to evaluate alternative circuit designs and redundancies or the effects of using components of different quality standards.

The calculated values can be compared with the data obtained from practical testing, with the burn-in and repair statistics, and with field experience. The results of this comparison may enable the development and design departments to improve such factors as circuit design, component selection or the production process. The results also indicate whether the numerical values and formulations used in the prediction calculation reflect reality.

A particularly important element of the prediction system, is the "component failure rate, experience/standard" file. The computer program on which it is based is used for determining component failure rates from the recorded field data. This part of the computer program additionally provides information as to whether and, in some cases, in which location within a module, clusters of component failures occur. Information about "fault concentrations" of this kind are passed on to the development departments in the form of diagrams or lists.

Component qualification – the key to equipment quality

An important objective in equipment development is to minimize the number of different types of components and to use the selected and qualified standard components in as many units as possible. This is the only way of achieving high volume production. It is also necessary in order to ensure that components can be procured smoothly and economically in accordance with the documented technical agreements and by inspection on the manufacturer's premises. These objectives are served by a number of standards, standard-related test programs and standardization and quality assurance procedures.

An exception are special microwave devices which are used in comparatively small quantities and require special test methods before they can be released.

Qualification of components in standard technology

For components in standard technology as used in the lower and middle frequency range, the electrical, mechanical and climatic characteristics as well as their quality level can be checked and laid down in accordance with the requirements specified. In addition, it is necessary to secure long-term supply capability and a second source of supply. Qualified preferred types are classified into status categories and assigned to a range of applications depending on their service life.

Standard components qualify by the following process:

Having applied for approval to the component department, the equipment development engineer initiates the qualification process which consists of a technological examination, a comparative performance test, a long-term test and a stress test. The long-term test provides information on reliability. Evidence of anticipated service life may be provided by national or international standard-related test procedures. These test results form the basis of technical conditions of supply which are agreed with the component manufacturers. A DP system (**Fig. 4**) compiles the component data for equipment development and production and ensures that only qualified components can be incorporated in the technical documentation.

Incoming components pass through the factory's receiving inspection department which establishes the quality of the items supplied using detailed test specifications and test programs. If the components are covered by national or international standards, the documented procedures of the manufacturer can also be used as evidence of quality, particularly if the manufacturer is approved under the CECC's European Harmonized System of Quality Assessment for Electronic Components.

Qualification of microwave components

Microwave components with their special technologies and high-quality materials require additional qualification tests. Important parameters include the material properties, thermal characteristics and electrical operation as a function of frequency. Available test methods include examination by scanning electron microscope, X-ray spectrometry, thermography and frequency spectrum analysis. The spectrum analyzer is used to check the required power output within the operating frequency range and to detect any parasitic oscillations and spurious frequencies. Specially prepared microwave components are examined by X-ray spectrometry to ascertain their material structure and passivation. The scanning electron microscope reveals material voids, mask errors, poor adhesion of the metallization and bonding, as well as case defects (**Fig. 5**).

Contactless measurements under the infrared scanning electron microscope show the temperature distribution and indicate the location and extent of areas of critical local heating on the semiconductor surface (**Fig. 6**).

A programmable scanning system enables the temperature field to be represented with a high localized resolution of 10 µm. A desktop computer controls the measuring process and evaluates the results.

The components are exposed to different environmental stresses in accordance with specified test programs based on national and international standards and are then checked for conformance to their functional parameters (**Fig. 7**).

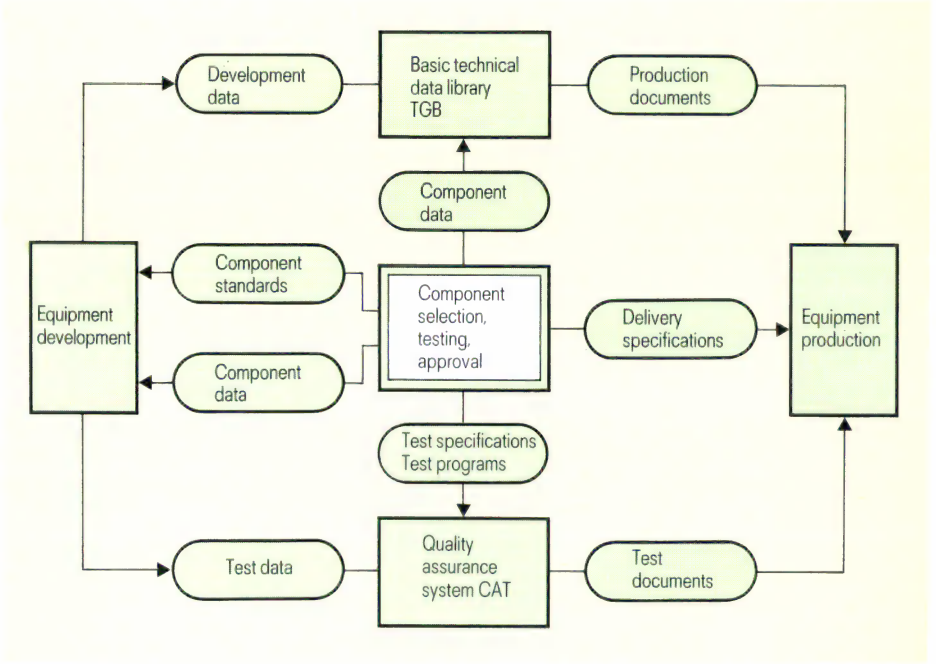


Fig. 4 Computer-controlled component data compilation system

Fig. 5 Scanning electron microscope with X-ray spectrometry can detect physical defects in microwave components

This provides information about the anticipated operational reliability and utility life (generally 15 to 20 years).

Quality is obtained by staying within stress limits

The electrical stress on components and the ambient temperature are the factors which largely determine the failure rate of a module. **Fig. 8** shows these relationships for a module in a 140-Mbit/s protection switching equipment. Except for the integrated circuits, all the components had their stresses jointly varied by between 10 and 90% of the permitted operating maxima. The reference point – the failure rate of "one" – is the failure rate of the module with 30% electrical stress and 25 °C ambient temperature (T_{am}); the overtemperature inside the switching inset relative to the ambient temperature was estimated at 15 K. The disproportionate rise in the relative fail-

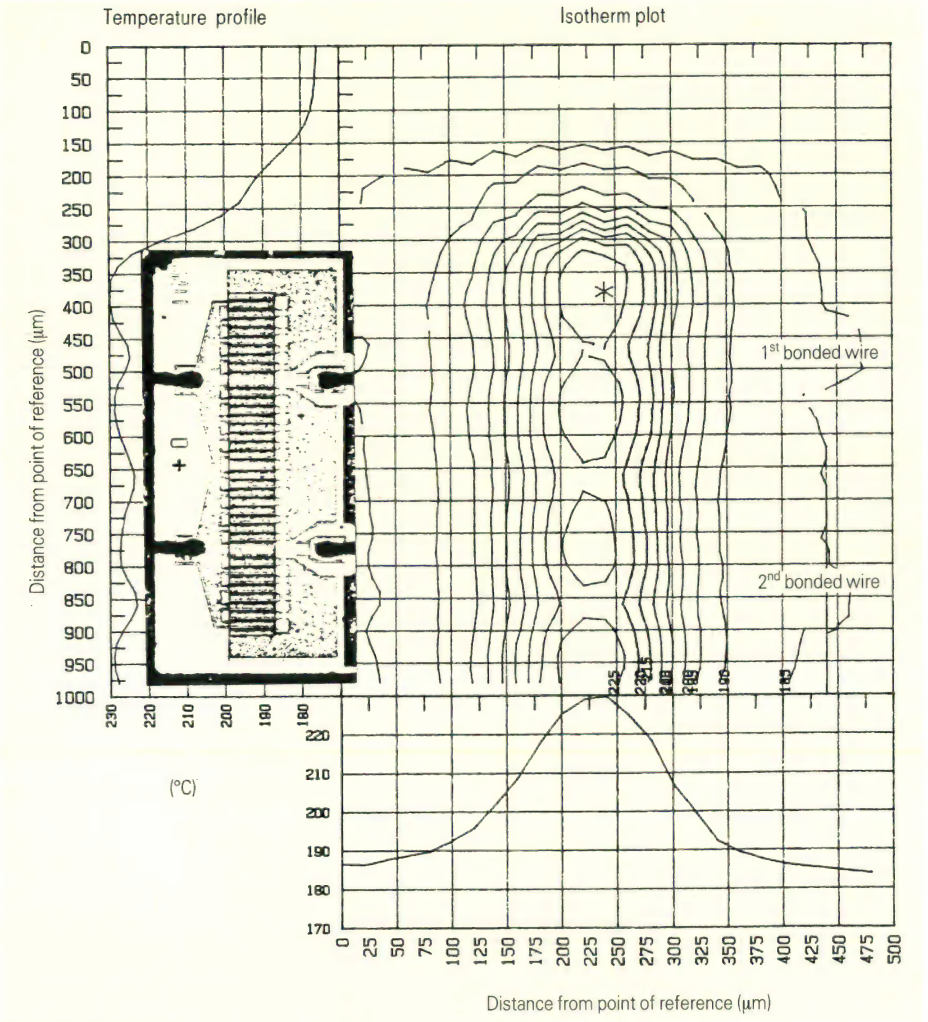


Fig. 6 Temperature profile and isotherms of a microwave transistor in GaAs technology, obtained using the infrared scanning microscope

Fig. 7 Testing station for performing lifetime and reliability tests on components, particularly microwave devices

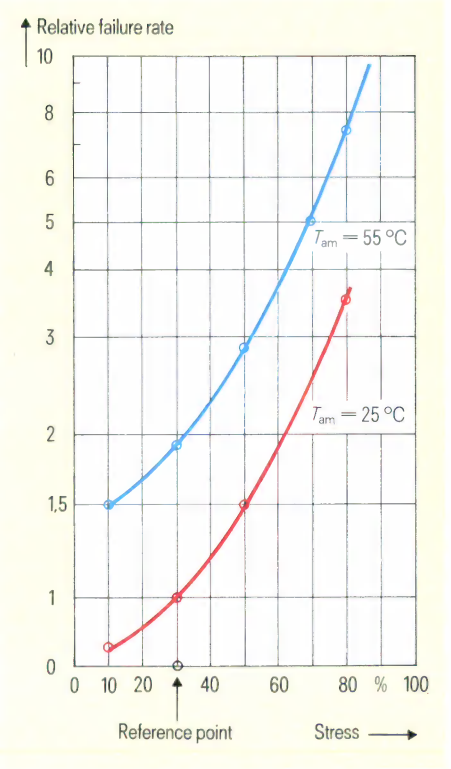


Fig. 8 Failure rate as a function of stress

ure rate with electrical stress is clearly discernible. The engineer developing transmission modules must therefore take care to ensure that, where possible, the relative stresses on components do not exceed 30% of their permissible values. A comparison of the curves for ambient temperatures of 25 and 55°C illustrates the similarly disproportionate rise in failure rate with increasing ambient temperature for the same electrical stress.

Practical values for the temperature distribution on the module can be obtained from thermographic analysis (**Fig. 9**). The surface of the item under test is scanned line by line and the test signals are displayed via an infrared detector and analysis electronics as a thermal image on a color monitor.

By way of example, **Fig. 9a** shows an RF amplifier and **Fig. 9b** shows its thermographic color image on which the outlines of the module sections and their temperatures can be recognized as areas of different color.

Violet corresponds to the lowest and red to the highest temperature range, with several intermediate ranges each $\Delta T = 2\,K$ wide. The central section of the module has a relatively high tempera-

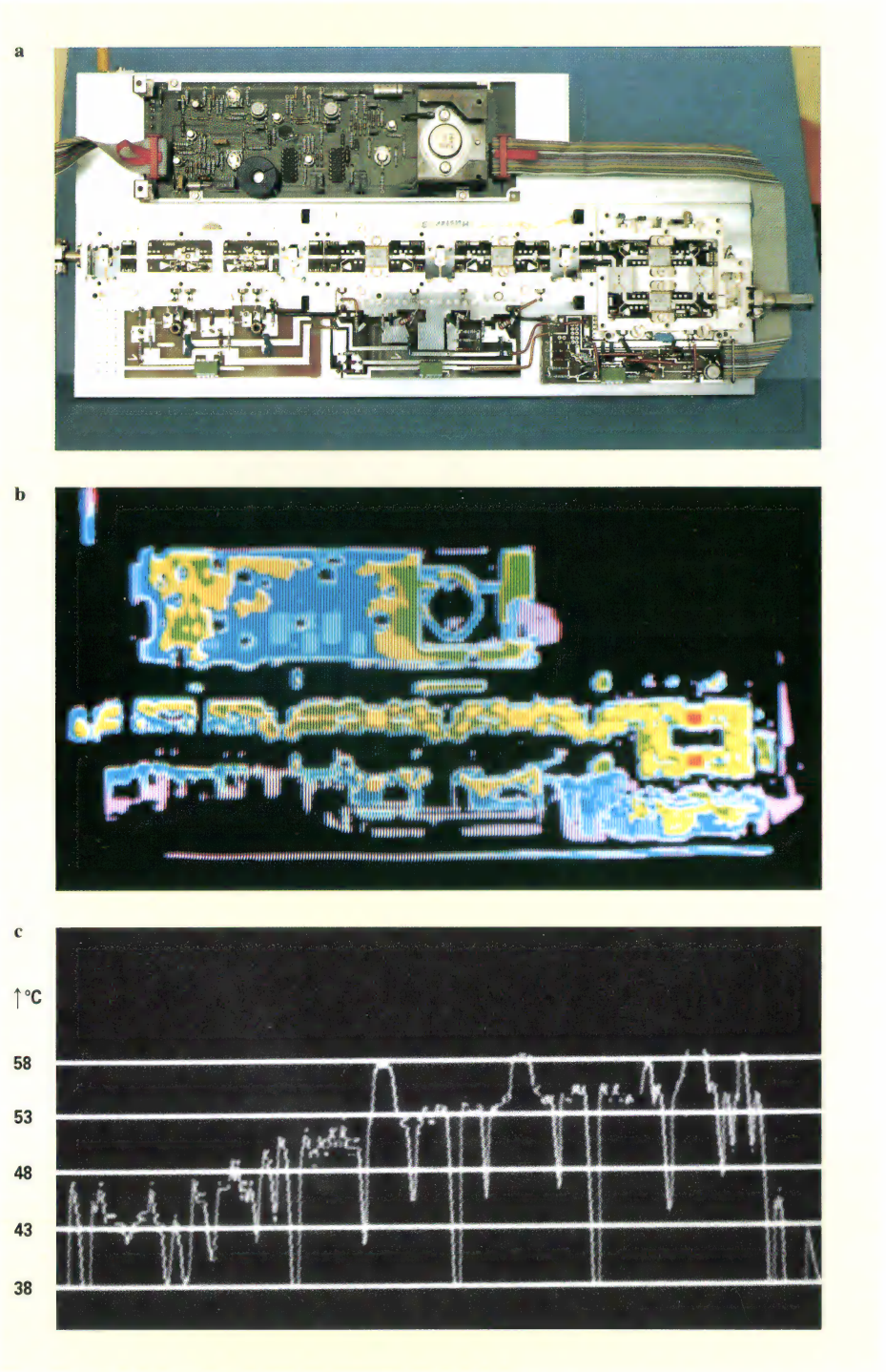


Fig. 9 Thermographic analysis of a 6.7-GHz RF amplifier (a) with its thermal image (b) and one of its temperature profiles (c); power consumption 37 W, reference value for the overtemperature: ambient air 27 °C

ture level indicated by yellow and red. One of the scanned lines was therefore analyzed in detail and displayed on a second monitor as a temperature profile (**Fig. 9c**). The calibration lines are each spaced 5 K apart; the localized resolution is less than 100 µm.

In order to ensure high reliability, this imaging technique can be used to detect and eliminate "hot spots" right at the development phase.

Qualification and testing – prerequisite for product release for production

A comprehensive series of tests and qualification testing ensure that transmission equipment operates reliably

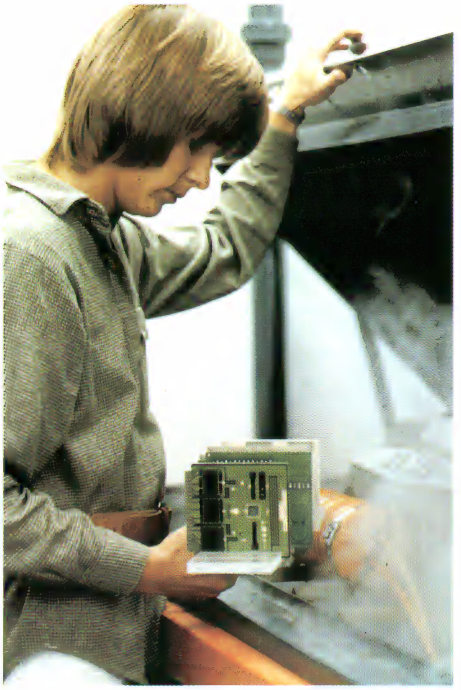


Fig. 10 Corrosion resistance testing is an important part of testing in simulated environments to determine material and performance limits

even under extreme service and environmental conditions and that all the guidelines, specifications and safety requirements are satisfied. These activities begin early on in the process and are performed at each stage of product development in cooperation with Quality Assurance and the Central Testing Department of Siemens Central Laboratory for Communication Engineering.

Accordingly, preliminary performance characteristics are tested on development models even at the development stage and on system components in a simulated environment in order to detect material and performance limits and to reveal possible weaknesses early (**Fig. 10**). Special test methods or equipment often have to be developed and tested first in order to verify product characteristics reliably. Automated computer-controlled test and recording equipment is used to assimilate and store the mass of test data, thus ensuring that all results, particularly in the case of repetitive measurements, are objective and comparable.

With some 4000 m^2 of floorspace, the Quality Center in Munich has all the facilities for simulating mechanical, climatic and electromagnetic environmental effects, together with equipment for functional testing and materials

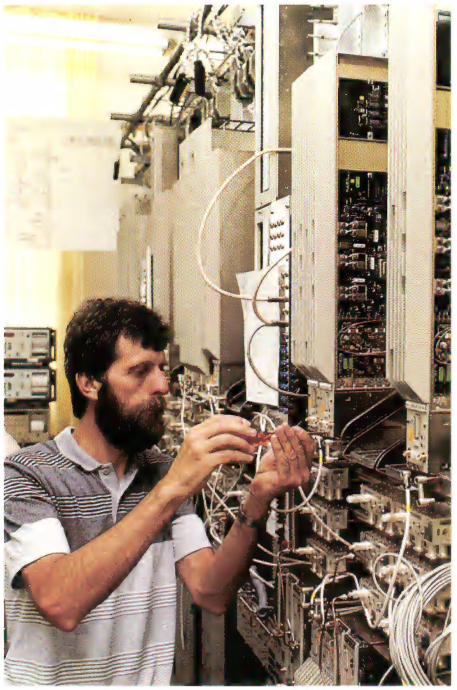


Fig. 11 Diagnostic test bench for a 140-Mbit/s radio relay system

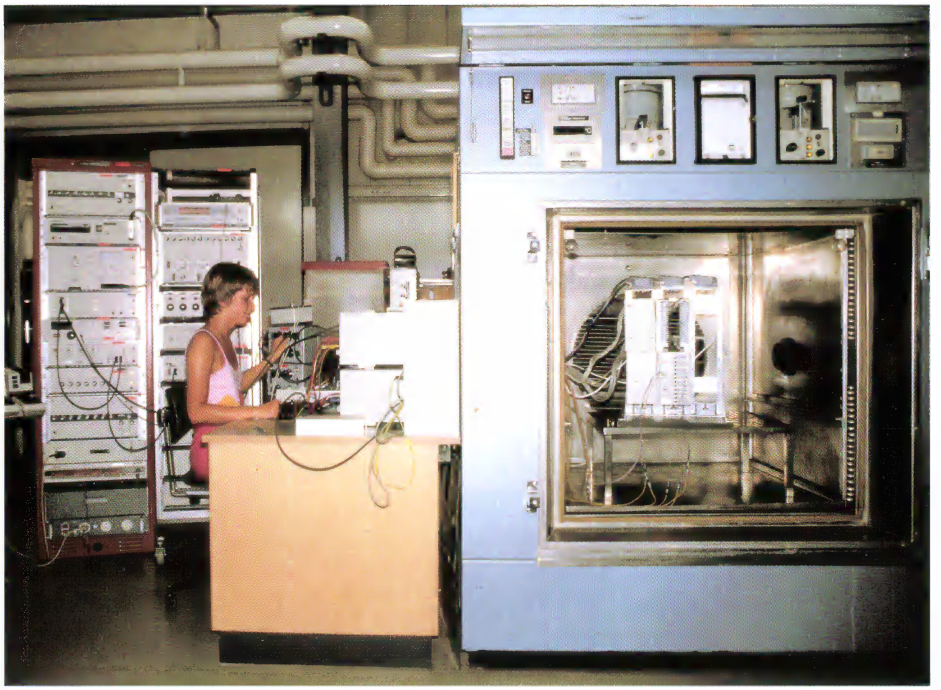


Fig. 12 Module undergoing climatic testing under operating and limit conditions

analysis. The facilities even provide for simulating extreme service conditions. There is a separate specialized laboratory for type testing of radio communication systems (**Fig. 11**). Here, modules and sections undergo comprehensive functional testing prior to system integration.

Parallel to this, equipment is tested under operating and limit conditions. In addition to climatic and mechanical stress testing (**Fig. 12**), the tests to verify electromagnetic compatibility (EMC) are particularly important (**Fig.** p. 268). These involve extensive measurement of emitted radio frequency interference and verifying immunity to external fields and interfering signals. The test program naturally also includes tests for packing, shipping and storage.

The latest analytical methods, such as fluorescence microscopy, SEM microscopy (**Fig. 5**) with X-ray spectrometry and infrared spectroscopy, are available for selecting and optimizing the required materials and components and for analyzing any damage.

Thus, all communication products are rigorously tried and tested at each stage, from design model to volume production, in accordance with national, international or customer specifications. Experience gained over many years from damage analysis and evaluation, a highly qualified staff and the organizational independence of the Quality Center ensure that all the results are assessed objectively.

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Günter Zefferer

Quality Assurance in the Development of Software for the C450 Mobile Radio System

The quality of an industrial product is determined by the quality of development and production. Since software products do not involve a production process, their quality is determined solely by the development process. This process must incorporate all phases of quality assurance [1 to 3] with particular emphasis on the functions, technical quality, cost (resources) and timing aspects of quality.

These aspects are considered in the following article which describes the planning and controlling of the project to develop software for the base stations (BS) employed in the C450 mobile radio system.

Dipl.-Math. Günter Zefferer,
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Data Systems, Munich

Development process

The overall development process was based on the *product* and *project* structures established separately for both hardware and software. In the following paragraphs, consideration is given only to the software structure. This is shown in **Fig. 1**.

Product structure

The *product structure* refers to the hierarchical breakdown of the system into manageable entities. The structure of the software for the base stations breaks down into six levels with the following contents:

- software system with its sets of functions [4],
- computer systems,
- sets of computer functions,
- subsystems,
- programs,
- modules.

The product structure through to the subsystem level comprised 128 elements and formed the basis for the planning.

Project structure

The *project structure* includes all activities of significance in developing the product. The main classes are:

- system design,
- development,
- procuring the test tools,
- integration and testing,
- configuration management,
- documentation,
- commissioning,
- quality assurance,
- planning.

The product and project structures were both detailed and formed the basis for the overall development process. The two linked to derive work packages which were defined in terms of the result to be achieved. Each work package was followed by a particular subresult for the product, defined precisely in form and content.

Both structures allowed frequent plausibility checks to be made. This ensured that all activities were implemented and that all results could be incorporated in the product structure.

Process structure

A third structure, the *process structure*, controls the development sequence which was arranged in *phases* in accordance with the conventions. At each phase, the work packages derived from the product and project structures were defined with their results (**Fig. 1**). Since the results derived from the structures were clearly stated, they provided a basis for direct comparison, thus creating a clear idea of what was to be achieved in the minds of those involved in quality assurance and further development activities (subsequent phases).

For the *design phases*, it was necessary to define precisely the documents required in terms of form and content.

This ensured that the documentation was continuous and largely free of redundancy, while providing a full description of the product. Consideration also had to be given to phase progression in order to ensure that all results provided the relevant information for phase completion in the required detail.

In the *engineering phases*, it was the testing that had to be defined. This was

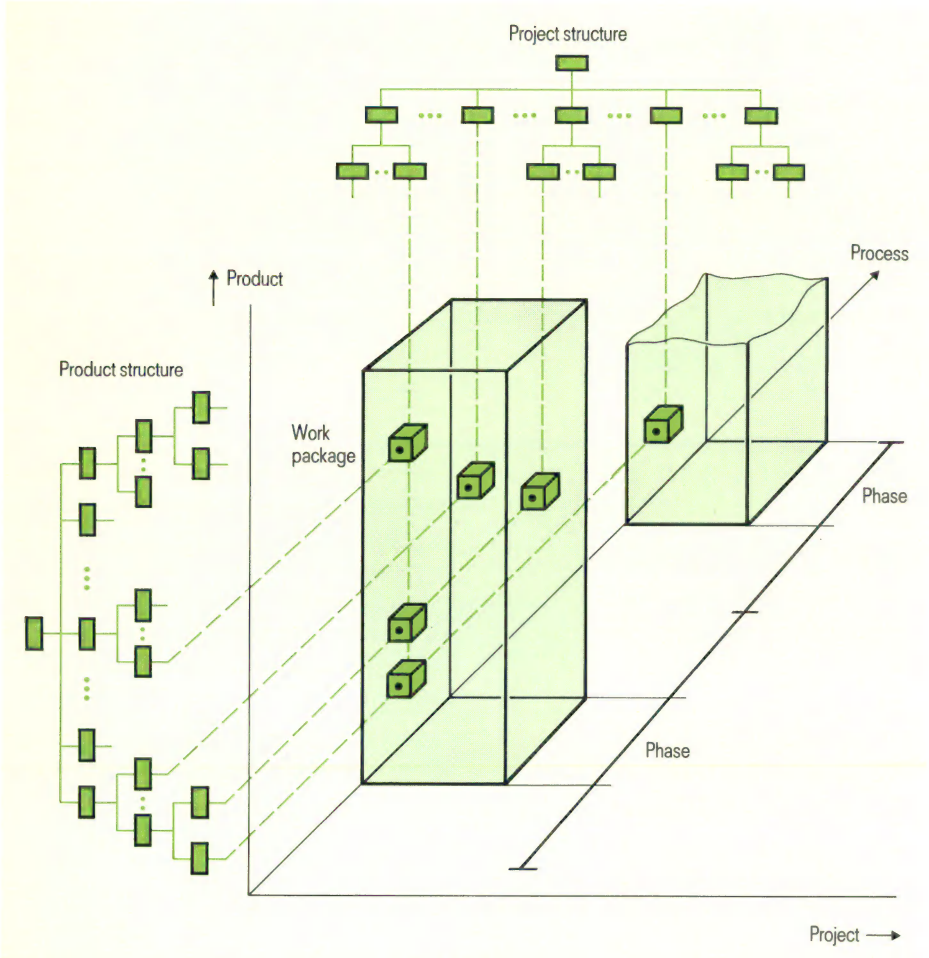


Fig. 1 Development process structures

necessary because of its dependence on the product structure.

These phases had the following test objectives:

- M test: testing all operating sequences in a module
- F test: testing one or more functions
  - F1: in a set of computer functions,
  - F2: in a set of functions via several computer systems,
  - F3: in the BS system,
  - F4: in the C450 system (code completeness)
- I test: testing the interaction of all functions
- S test: testing the C450 system under field conditions.

As with many major projects it was necessary to subdivide the development process into *subprocesses*. These were managed as subprojects for the purpose of developing product components. All the subprocesses were governed in all respects by the agreed conventions and were oriented to the objectives of the overall process.

Conventions

In major projects people with different experience are employed on various jobs. A development project will, therefore, only be successful if certain conventions regarding the *approach*, the *results* and *cooperation* are observed. The *approach* is characterized by structuring the development process by product, project and phases to produce work packages of manageable size and risk with clearly defined results. Defining the *results* by content and form ensures that different development departments present comparable results. This is the only way in which a qualified review and a reliable status statement can be made. Finally, good *cooperation* is dependent on the quality of the communication. This ranges from the joint document review, the coordination of and release of completed parts of the project through to reporting. Thus, good communication is crucial to process quality.

All the conventions required for this purpose were laid down in a development manual and a production manual. They were based on the guidelines proven in other projects and were adapted to suit the particular requirements of this project. These conventions and their application were agreed upon and implemented by all those involved in the project.

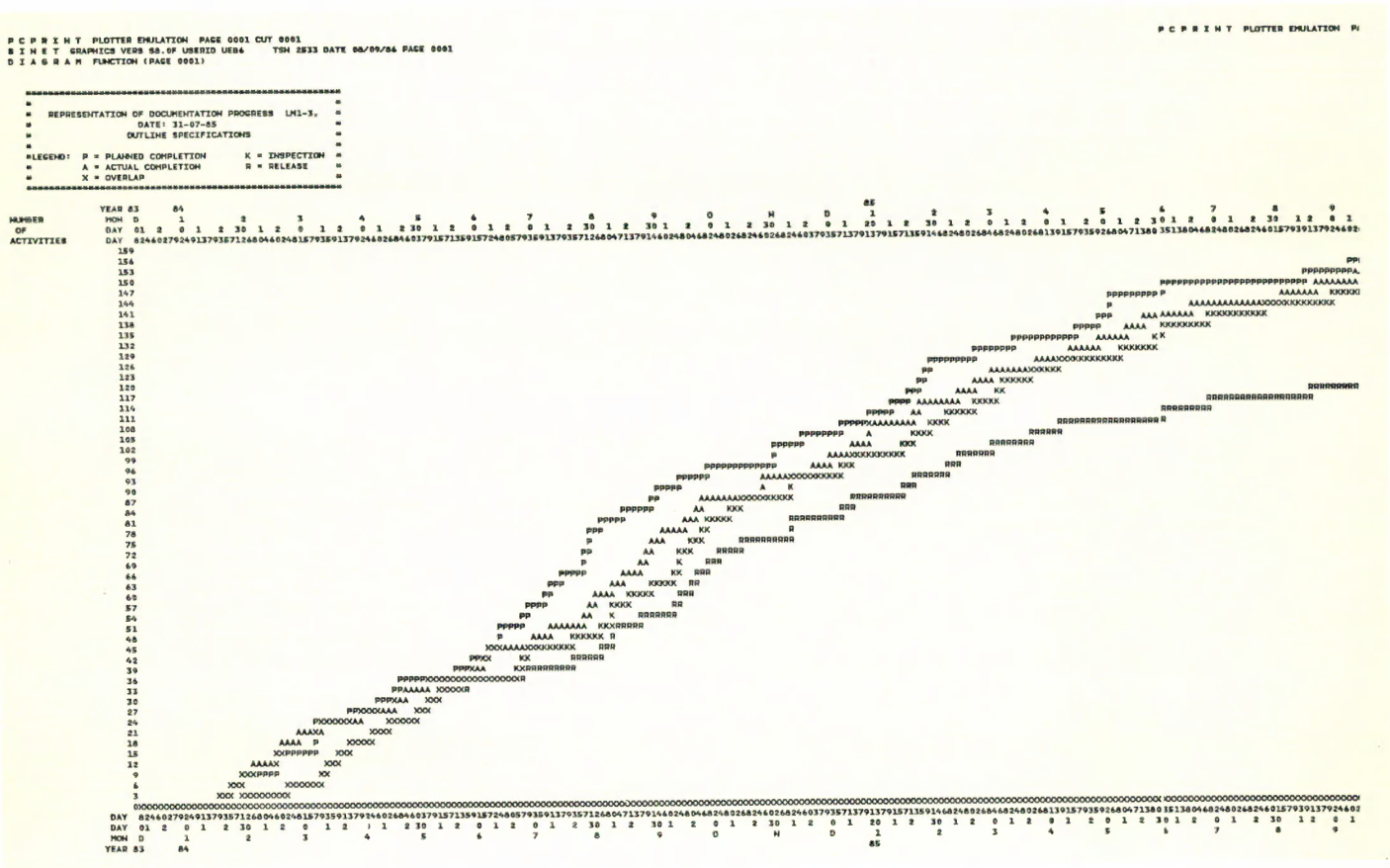
Planning, controlling and reporting

Since the planning was based on the structures defined in the development process, the work packages were integrated into the planning, thus ensuring its completeness. Being linked to the product structure, the planning focuses directly on the product under development. The phases provided for a step-by-step approach based on significant milestones of progress.

All the work packages were checked to establish their logical interrelationships and the latter – together with processing times and resource availability data – were incorporated in the network analysis diagram. This contains all the data for the entire project, including all subprojects, thus permitting central monitoring and control.

All planning data were kept in a central database, permitting analysis from different perspectives. This ensured that, when the planning was updated, all planned results remained consistent. Moreover, the interrelationships between various planning statements and the effects on all results were established immediately. The planning data were accessible by groups of objectives; also, the planning information was prepared in such a way that each development department received precisely the information it requires. This prevented the departments from being inundated with irrelevant information.

With a one to two year planning horizon and a two to three week update cycle it was possible to detect bottlenecks at an early stage and take compensatory action in good time. As a result, deviations from the planning amounted to no more than a matter of weeks even in critical phases of the project and could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R = RELEASE
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Fig. 2 Planned/actual comparison relating to the specifications

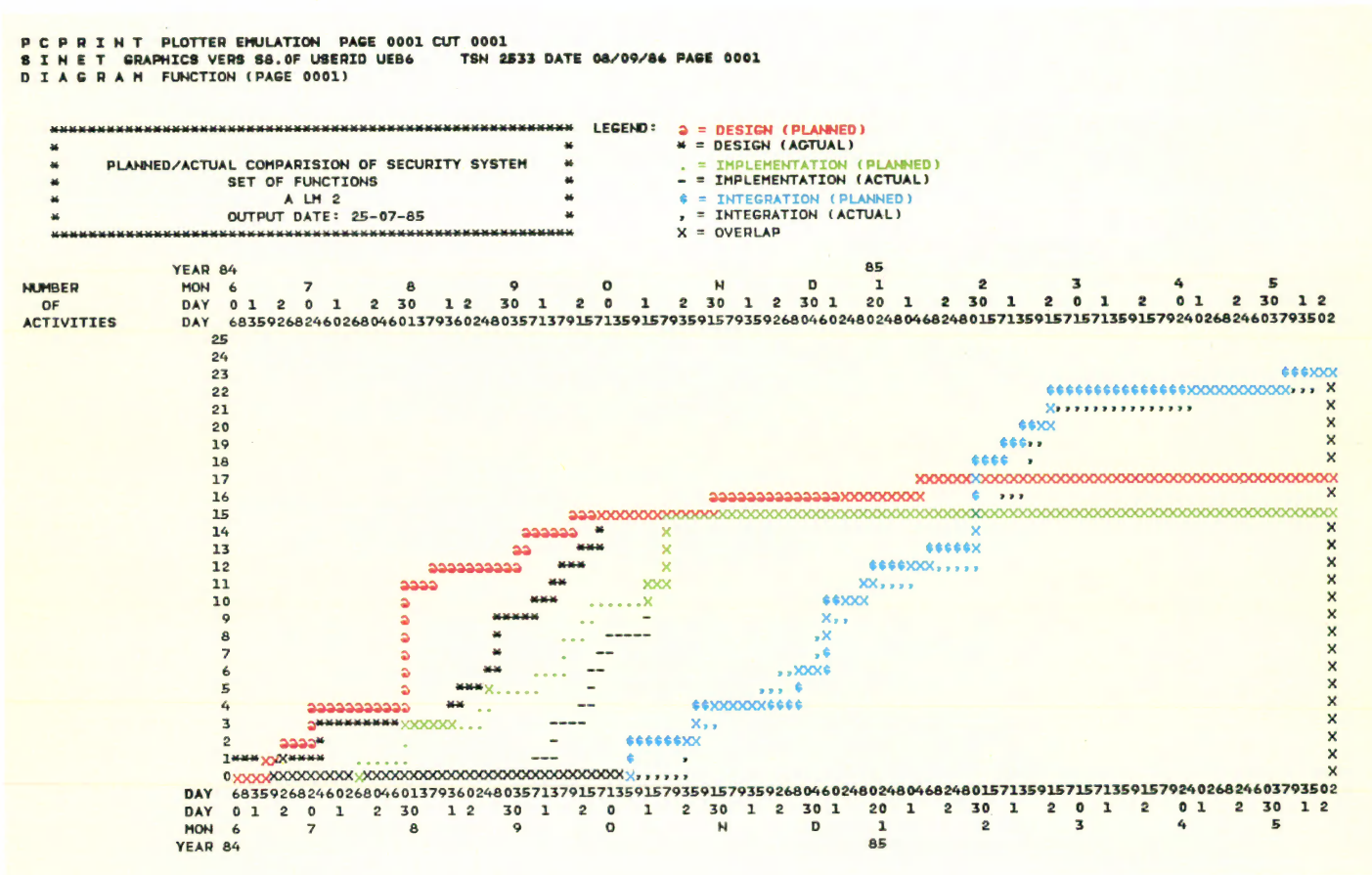

Fig. 3 Planned/actual comparison for the results of the "security system" set of functions

be compensated by taking appropriate action.

Since the planning was consistently based on the structures, the reporting system was organized on the same basis.

It was thus possible, for instance, to produce curves for certain phase results. **Fig. 2** shows a planned/actual comparison in respect of the specifications for the "system design" phase. It compares the planned submission dates for review of the documents with the actual dates and indicates the curves for "reviewed" and "released". In addition to this phase-oriented reporting there is also provision for product-oriented reporting. The comparison of planned/actual results for the ST (security system) set of functions in the "system design," "implementation" and "system integration" phases is reproduced in **Fig. 3**.

Reports could, therefore, be produced from different points of view. In addition, they not only stated the current position but also indicated trends from which it was possible to identify main areas for medium and long-term improvement.

Stage-by-stage quality assurance

The main areas of quality assurance are the

- *functional characteristics*

and the

- *technical quality of the results.*

The first step in assuring quality was to establish the functional characteristics and to check them in comparison with the product specification. Thereafter, all results of the development process were continually reviewed by reference to the functional characteristics. This required characteristics and phase results to be correlated right from the planning stage. Indeed, this was done consistently and monitored by quality assurance. Since the correlation was effected via the linkup with the planning data, it was possible to provide an update of it for each of the relevant work packages.

The *quality of the results* was established from the initial phases through to program design by reviews. Participants in these reviews were not only the development engineer, but also quality assurance and system engineering representatives as well as all the interfacing associates. The purpose of the reviews was to check and release the technical results, which meant that some reviews involved a number of steps.

When the review lead to release, the results were considered to be agreed and mandatory for the next development stage. Modifications after this point had been reached could only be made by submitting change requests. These were treated as functional characteristics which were incorporated in the planning and monitored through all the development stages. The performance status was thus clearly identifiable at each stage of development.

In the implementation phases, quality assurance took the form of selective tests which had been defined precisely in test specifications during the design phases.

Conclusion

The approach described ensured that the quality aspects were continually reviewed and that all employees were involved in quality assurance. The procedures were coordinated and continuous. Since the results produced were used as an additional input to control the development process, it was possible to take action to eliminate quality defects at an early stage. The risks involved in the development process were thus calculable at every stage and it was possible to meet the objectives in all respects even with development times of more than two years. The development quality achieved produced very good system stability during first field use, so that the problems, which naturally occur in such situations as a result of the physical conditions of the link, could be identified and eliminated rapidly.

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Ludwig Hadersdorfer

Quality Assurance in the Radio Production Facility

One of the basic requirements for any production operation is to manufacture products of consistent quality at competitive cost. The specified product quality is attained by quality assurance organized as an independent control function acting across divisional boundaries. "Assuring product quality" means not only making sure that the product conforms to specifications under the required environmental conditions, but also ensuring that the product will meet the required failure criteria within the planned service life. The latter objective requires that, at every stage of the production process, quality control procedures should accompany the product from reception of its component parts through to its final inspection in the system test department.

This article discusses the quality assurance concept underlying the production process in the Radio Production Facility in Munich; in addition, the quality assurance procedures implemented at the individual stages in the process are described in production-flow sequence.

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Munich

Quality assurance concept

The quality assurance concept in the Munich Radio Production Facility is basically characterized by the fact that two mutually independent organizations are responsible for production and quality assurance. The production process is organized as a continuous process with a number of stages, such as component and materials receiving, parts production, surface treatment, various assembly stages through to module and system testing on the finished products [1, 2]. Quality assurance, on the other hand, is a kind of network superimposed on the production process and has set up QA gates between the successive production stages, starting with the receiving department. At these gates, the starting quality of the particular stage is controlled with the primary objective of detecting errors or defects in the production flow as early as possible.

Within this concept, the test departments associated with the quality assurance organization perform a dual role. For module and system alignment operations, they are fully integrated in the production process, but at the final inspection they are part of the quality assurance organization, ensuring conformance to the specifications under the required environmental conditions. However, as a result of automatic final testing with computer-generated records being introduced in the Munich Radio Production Facility, the test departments can do full justice to both functions without any conflict of interest, since the automatic recording of results eliminates the subjective influence of the tester. Final testing of the products therefore assumes the full character of a quality assurance gate as referred to above.

Quality assurance in the receiving department

Purchased components account for more than half of the entire cost of radio relay equipment. Assuring the quality of these items (raw materials, semi-finished products, standard parts, components) is therefore of paramount importance. The approach adopted is to draw up agreements with suppliers based on suitable specifications in order to assure quality on the producer's premises. However, the quality required for radio relay equipment is frequently not available on the market and the commercially available AQLs (acceptable quality levels) are inadequate. Consequently, a large proportion of the components undergo a 100% receiving inspection, covering aging, temperature shock and solderability tests as well as the electrical characteristics. For each item purchased, there is an inspection plan. This is based on the continuously monitored quality rating of the vendor and on the specified limit values and lists the tests to be performed for all the functionally important parameters.

All the components are stored by lots and used on the FIFO principle (first in – first out) so that they can be traced in the event of subsequent complaint.

Mechanical parts production

The level of automation in the mechanical parts production department is very high due to the use of numerically-controlled machine tools. Consequently, the mechanical products there are only controlled on a sampling basis to specified AQLs. Specially trained quality control personnel inspect the manufactured pieces for conformance to their required geometrical dimensions,

Fig. 1 Computer-controlled 3-coordinate CNC machine for three-dimensional testing of mechanical precision products

characteristics and functions using the latest measuring equipment (**Fig. 1**).

In addition, products from subsequent operations, such as soldering, riveting, welding or electroplating must be assessed according to various criteria. Further, mechanical, optical and electrical tests are performed on printed circuit boards.

Quality assurance at the assembly stage

In the assembly departments, modules and units are subjected to continuous in-process inspection. The following aspects are tested:

- mechanical component processing (bending, cropping),
- condition of soldered joints,
- condition of mechanical parts,
- mounting of electrical and mechanical components,
- unit assembly and
- wiring.

A sampling check is generally performed after each operation within a production stage, and a detailed inspection is carried out after several operations. All the inspection procedures are contained in the production plan which describes each step in the manufacturing process. In addition to these scheduled tests, a roving inspector patrols the individual workstations to verify that the assembly work is being carried out correctly and carefully.

The criteria for assessing the process steps and the workmanship are defined in detailed, illustrated manufacturing specifications. Comprehensive computer-generated defect statistics are made available in several levels of detail for suitable control of the quality assurance procedures.

In addition to a rigorous receiving inspection followed by systematic checks in the assembly departments and expert testing of mechanical products, there is a further quality assurance gate in the form of in-circuit testing at the point before the modules pass to the testing department. This is required in order to eliminate final "hidden" defects.

Unit and system testing

The final electrical test is designed to guarantee the customer trouble-free operation of the product. For economical testing of these products, the final test departments are equipped with computer-controlled test setups and automatic testing equipment (**Figs. 2** and **3**). The computer programs establish both the type and sequence of tests as well as the use of the test equipment, circuits, etc., thus largely eliminating test and reading errors.

During testing some of the units are placed in climatic test chambers so that measurements can be performed across the entire temperature range specified. A subsequent burn-in test, lasting 168 hours over several temperature cycles and accompanied by measurements on important parameters, detects the early failures.

All the test results are recorded, evaluated and printed out automatically, thus eliminating any bias on the part of the tester.

Calibration of electrical and mechanical measuring equipment

As part of "Siemens' Calibration Service", the internal calibration laboratories provide for regular checking of electrical and mechanical measuring equipment. The measuring equipment is recorded on computer and called in for calibration at the appropriate time. The equipment is then checked for accuracy and, if necessary, adjusted or sent for repair. Test certificates provide docu-

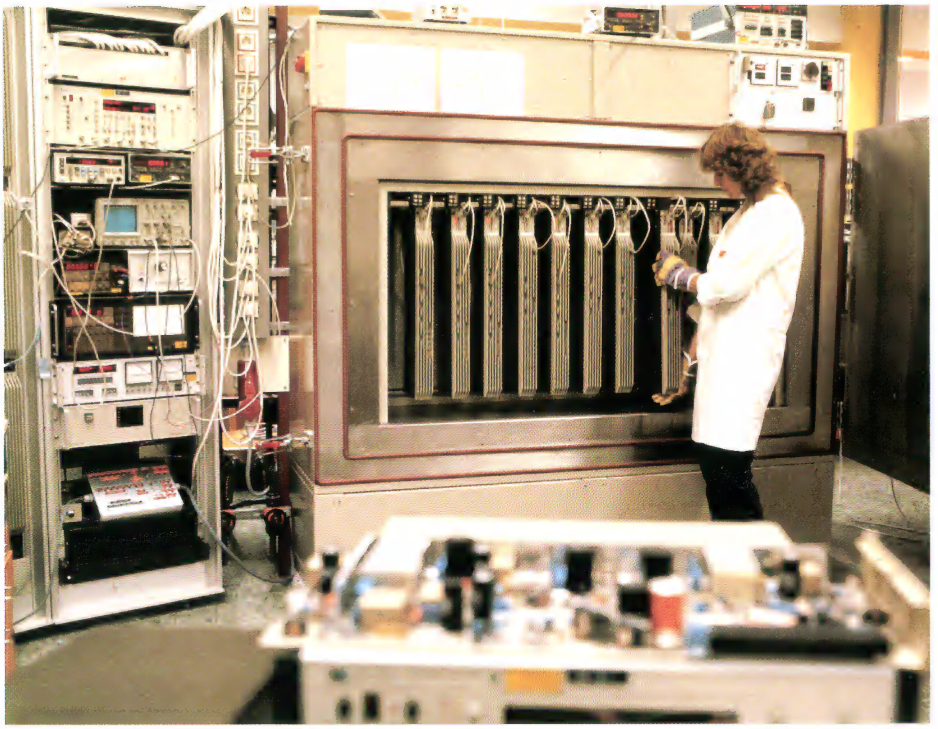

Fig. 2 Burn-in system for radio relay equipment insets, monitored by computer-controlled test setups

Fig. 3 Automatic tester for checking the RF sections of digital radio relay systems operating in the 13 to 18 GHz range

mentary evidence of proper compliance with calibration procedures. Calibrated units carry a sticker indicating when the next test is due.

Prospects

The independent nature of the quality assurance organization is the guarantee of uniformly high product quality. Careful testing accompanies all stages of production. Increasing automation in the production and quality areas will progressively reduce human bias in the test results, thereby making a further contribution to the quality of Siemens' products.

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Braun, Gerhard

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Keil, H.; Künemund, F. SIEMENS

Development Trends in Radio Communication

5 figures, 28 references

telcom report 10 (1987) Special "Radio Communication," pp. 5 to 10

Establishing communication links rapidly is a province of radio communication, since only transmitting and receiving equipment needs to be set up for the purpose. Radio communication is subdivided into three major fields: satellite communication, radio relay and mobile radio systems. The article deals with the development trends in these fields.

Descriptors: radio communication; satellite communication; radio relay; mobile radio systems; digitization; development trends

Noack, W.; Thaler, H.-J. SIEMENS

Planning Considerations for High-Capacity Digital Radio Relay Systems

9 figures, 5 tables, 3 references

telcom report 10 (1987) Special "Radio Communication," pp. 31 to 40

In this contribution on planning considerations for digital radio systems, the authors review performance and availability objectives of the CCITT and CCIR and discuss the main effects and mechanisms that degrade performance and availability. In the main section all significant contributions to system impairments by noise and interference are discussed. These considerations lead to guidelines for the required isolation and discrimination values against interference. Finally, a brief review of dispersive fading effects is given.

Descriptors: quadrature amplitude modulation (QAM); performance and availability objectives; dispersion models; signal-to-interference ratio (*S/I*)

Fink, G.; Köttgen, B.; Wolf, E. SIEMENS

Radio Communication – an Innovative Market

4 figures

telcom report 10 (1987) Special "Radio Communication," pp. 11 to 16

From a sales standpoint, this overview article describes the current status of the various areas of radio communication – satellite communication, radio relay, mobile radio systems and special-purpose networks – and gives the prospects for further development in this field, with particular reference to the Siemens company.

Descriptors: radio communication; innovation; satellite communication; radio relay; mobile radio; special-purpose networks; quality requirements

Dittl, K.; Molin, M. SIEMENS

Narrowband Radio Relay Systems

7 figures, 1 table, 3 references

telcom report 10 (1987) Special "Radio Communication," pp. 41 to 46

Radio relay systems for the transmission of digital signals at 2 or 8 Mbit/s are employed predominantly in medium-haul PTT networks and in private networks. The existing series of radio relay systems for analog transmission of 24 to 300 voice channels has been augmented by a series of systems for digital transmission in the frequency bands 800, 1800, 7200 and 7500 MHz. The concept, design and operation of these narrowband radio relay systems are described.

Descriptors: narrowband radio relay system; digital transmission; frequency-shift keying (FSK); HDB3 coding; phase-locked loop (PLL); service channel in original band; hot standby

Riepert, H.-G.; Vögtle, G. SIEMENS

Munich Radio Production Facility – Modern Production Methods Assure High Quality

7 figures, 2 references

telcom report 10 (1987) Special "Radio Communication," pp. 17 to 21

Far-reaching measures were adopted in the Munich radio production facility for the large-scale production of sophisticated high-technology systems and equipment. These measures are made necessary by the production engineering requirements of components for ever-higher frequencies (up to 30 GHz), the increased reliability demands and the widely diversified product spectrum.

Descriptors: Munich radio production facility; production methods; assembly

Fischer, R.; Kloeber, P.; Lehmann, U. SIEMENS

Digital Radio Relay Systems for Short- and Medium-Haul Networks

9 figures, 1 table, 3 references

telcom report 10 (1987) Special "Radio Communication," pp. 46 to 51

Three radio relay systems have been developed for use in short- and medium-haul networks. Two of them operate in the 15-GHz band at bit rates of 2×8 (2×2) Mbit/s or 34 Mbit/s; the third, operating at a bit rate of 34 Mbit/s, is intended for the 13-GHz band. All these systems employ quadrature phase-shift keying (QPSK) with direct modulation of the RF carrier on the transmit side and coherent demodulation on the receive side.

Descriptors: digital radio relay system; short-haul network; medium-haul network; RF channel arrangement

Panschar, H.; Steinkamp, J. SIEMENS

State of the Art and Future Trends in Digital Radio Relay Systems

2 figures, 1 table, 16 references

telcom report 10 (1987) Special "Radio Communication," pp. 23 to 30

Present and future transmission capacity requirements can be met by developing a second generation of digital radio relay systems employing higher-density modulation schemes and adaptive techniques for optimizing transmission, by consistently applying new technologies and by increasingly exploiting the frequency bands above 11 GHz.

Descriptors: digital radio relay systems; digitization of the telephone network; 1st generation systems; 2nd generation systems; frequency economy; modulation methods; use of new technologies

Fischer, R.; Kloeber, P.; Lehmann, U.; Thaler, H.-J. SIEMENS

Digital Radio Relay Systems for Local Networks

9 figures, 1 table, 8 references

telcom report 10 (1987) Special "Radio Communication," pp. 52 to 58

Describes a new family of systems providing transmission capacities of 2, 8 and 34 Mbit/s in the frequency range 17,700 to 17,900 MHz. The units are designed for use as easily set up alternatives to cable systems in the local network area. As the hop lengths are limited due to rain attenuation, the units are designed for mounting close to the antenna and outdoor operation.

Descriptors: digital radio relay system DRS 2-8-34/18700; local network in 18-GHz band; transmission capacity of 2 to 34 Mbit/s; FSK modulation

Gernegross, D.; Oberparleiter, K.; Ulmer, W. **SIEMENS**

Digital Radio Relay Systems for the Transmission of 34-Mbit/s Signals

12 figures, 1 table, 8 references

telcom report 10 (1987) Special "Radio Communication," pp. 59 to 68

In the long-haul network, radio relay systems are usually operated in the frequency bands below 10 GHz in order to ensure reliability in spanning the hop length of some 50 km recommended by the CCIR. The new OQPSK modem (offset quaternary phase-shift keying) for transmitting 34-Mbit/s signals has been implemented using semi-custom, large-scale integrated CMOS circuits.

Descriptors: digital radio system; long-haul network; digital radio relay system family DRS 34/1900-2400-2600; digital radio relay system family DRS 34/6700-7500-8400; OQPSK modem

Barth, H.; Kahn, K.-D.; Nossek, J.; Sebald, G. **SIEMENS**

QAM Digital Radio Relay Modems for the Transmission of 140-Mbit/s Signals

17 figures, 1 table, 23 references

telcom report 10 (1987) Special "Radio Communication," pp. 68 to 79

Multilevel quadrature amplitude modulation methods (16 QAM, 64 QAM) are employed in order to obtain efficient utilization of the available frequency band. Since complex transmission techniques of this type are very sensitive to linear distortion of the digital signal it is necessary to provide adaptive equalization of the received signal. This equalization is achieved with an adaptive complex transversal filter operating in the baseband section of the demodulator in response to time domain criteria.

Descriptors: digital radio relay modem; quadrature amplitude modulation; linear distortion; adaptive equalization

Lankl, B.; Nossek, J.; Sebald, G. **SIEMENS**

Cross-Polarization Interference Canceller for Multilevel QAM Digital Radio Relay Systems

10 figures, 9 references

telcom report 10 (1987) Special "Radio Communication," pp. 80 to 85

Cross-polarization interference cancellers (XPICs) provide additional means of enhancing cross-polarization discrimination (XPD), which must be high for cochannel operation with high-level modulation schemes. XPICs must operate on the two plesiochronous data signals transmitted in two orthogonal polarizations so that the justification and synchronization of the two signals is unnecessary. This is particularly advantageous for 16-QAM systems with 40-MHz channel spacing in the RF bands at 3.9 GHz, 4.7 GHz, 6.7 GHz and 11.2 GHz.

Descriptors: cross-polarization interference canceller (XPIC); cross-polarization discrimination (XPD); fractionally-spaced transversal filter; high level QAM

Amend, W.; Simon, H.-O.; Thaler, H.-J.; Vogel, K. **SIEMENS**

Family of Digital Radio Relay Systems with 16 QAM for 140-Mbit/s Transmission in Long-Haul and Medium-Haul Links

10 figures, 2 tables, 13 references

telcom report 10 (1987) Special "Radio Communication," pp. 86 to 97

The article describes the radio sections of four digital radio relay systems for transmitting 140-Mbit/s signals. The units operate in the 2900, 4700, 6700, 11200, 13000 and 15000 MHz frequency bands. All six systems employ sixteen-level quadrature amplitude modulation (16 QAM). Modulation and demodulation occur at the intermediate frequency of 140 MHz.

Descriptors: digital radio relay system; long-haul system for 140 Mbit/s; radio frequency unit; RF channel arrangement; quadrature amplitude modulation (16 QAM); system characteristic

Küchler, H.; Peterknecht, K.; Ulmer, W.; Vogel, K. **SIEMENS**

Family of Digital Radio Relay Systems with 64 QAM for 140-Mbit/s Transmission in Long-Haul Links

7 figures, 1 table, 7 references

telcom report 10 (1987) Special "Radio Communication," pp. 98 to 105

The system family presented in this article is designed for high-grade transmission of 140-Mbit/s signals on long-haul links. In compliance with CCIR and CEPT recommendations, these systems operate in the frequency ranges, 2.1 GHz, 3.9 GHz and 6.2 GHz, with channel spacings of 29 MHz, 30 MHz and 29.65 MHz. They employ 64-level quadrature amplitude modulation (64 QAM), since it is a standard and suitable modulation scheme for channel spacings down to 28 MHz. The advanced features of the systems introduced here enable the more effective use of the frequency bandwidth and network resources.

Descriptors: digital radio relay system; quadrature amplitude modulation (QAM); cochannel operation; RF channel arrangements

Otremba, K.; Steinkamp, J.; Thaler, H.-J.; Vogel, K. **SIEMENS**

High-Capacity Digital Radio Relay System Family for the 18-GHz Band

16 figures, 2 tables, 5 references

telcom report 10 (1987) Special "Radio Communication," pp. 106 to 115

Followed a review of the channel allocation plans for the 18-GHz band, basic system considerations, such as modulation format, spectrum shaping and RF concept, are then treated together with system planning aspects in connection with rain attenuation and depolarization. It concludes by considering system applications for long-haul trunk extensions and local connections, and by examining the relationship between availability, rain climate conditions, required system margin and possible hop length.

Descriptors: Digital radio relay system; quadrature amplitude modulation (QAM); system planning; system characteristics

Junghans, H.; Otremba, K. **SIEMENS**

Up- and Down-Converters for Wideband Digital Radio Relay Systems

7 figures, 5 references

telcom report 10 (1987) Special "Radio Communication," pp. 116 to 119

Converter circuits for wideband digital radio relay systems, unlike those for frequency-modulated analog radio relay systems, have to satisfy exacting amplitude and phase linearity requirements on account of the multilevel modulation techniques employed. Moreover, as the number of levels increases, these modulation techniques require increasingly higher signal-to-noise ratios, necessitating correspondingly lower receiver noise figures. These factors are discussed with reference to the DRS 140/6700 radio relay system.

Descriptors: DRS 140/6700 digital radio relay system; 16-QAM modulation technique; up-converter; down-converter

Ens, H.; Otremba, K.; Schweinberger, J.; Thaler, H.-J. **SIEMENS**

Linear RF Power Amplifiers for High-Capacity Digital Radio Relay Systems

10 figures, 3 tables, 13 references

telcom report (10) 1987 Special "Radio Communication," pp. 119 to 125

The performance of state-of-the-art microwave power amplifiers for use in high-capacity digital radio systems is reviewed. After the description of a typical GaAs FET power amplifier used in a 140-Mbit/s radio system with 16 QAM, emphasis is put on characterization techniques for amplifier nonlinearities including measured degradation of system characteristics.

Descriptors: digital radio relay systems; GaAs FET power amplifier; traveling-wave tube amplifier (TWTA); solid-state power amplifier (SSPA); multilevel quadrature amplitude modulation (QAM)

Barth, H.; Molin, M.; Schröcker, A.; Simon, H.-O. **SIEMENS**

Protection Switching Equipment for Digital Radio Relay Links

9 figures, 7 references

telcom report 10 (1987) Special "Radio Communication" pp. 125 to 130

Digital radio relay links, like their analog counterparts, are fully protected by an (N+1) protection switching system. Apart from providing effective equipment protection and improved transmission quality through the frequency diversity effect, the most important facility is the removal of traffic from a circuit for maintenance purposes. This facility is further enhanced by using a special hitless switch which enables a prearranged changeover to be effected without causing bit errors.

Descriptors: digital radio relay link; protection switching equipment; (N+1) protection switching equipment; (1+1) protection switching equipment; frequency diversity; hitless switch; equipment protection; drop/insert

Ensslin, G.; Herder, H.-H.; Schuster, R. **SIEMENS**

Channel Branching Filters for Wideband Radio Relay Systems

8 figures, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 146 to 151

The physical factors relating to filters and circulators are briefly discussed insofar as they are important for the design of channel branching filters. The authors then describe the electrical and mechanical design of modern channel branching filters with particular reference to the fabrication methods employed. Test results are given for channel branching filters used in the DRS 140/6700 digital radio relay system.

Descriptors: channel branching filter; band-pass filter; circulator; wideband radio relay system; digital radio relay system DRS 140/6700; filter tuning; resonator

Barth, H.; Reich, H.; Tiwald, E. **SIEMENS**

Service Channel Unit and Utilization of Digital Service Channels

4 figures, 1 table, 3 references

telcom report 10 (1987) Special "Radio Communication," pp. 131 to 135

High-capacity digital radio relay equipments employ a radio relay frame for supervising the link. This frame can be additionally used to provide service channels in digital form for no significant extra cost and without degrading the main signal. Many PTT administrations use these service channels for voice communication between the radio relay stations (engineering order wire) and for transmitting supervisory signals.

Descriptors: service channel unit; digital service channel; radio relay frame; signal degradation; engineering order wire; service channel capacity; (1+1) protection switching equipment; wayside traffic

Schuegraf, E.; Schuster, R. **SIEMENS**

New Types of Microwave Diplexers for Dual-Band Radio Relay Antennas

4 figures, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 152 to 156

The increasing demand for transmission capacity calls for radio relay systems with RF bandwidths exceeding 20%. Another possibility is for two radio relay systems operating in different RF bands to be combined in one dual-band antenna system. This article describes new polarization diplexers with symmetrical excitation of both polarizations for bandwidths up to an octave.

Descriptors: microwave diplexer; RF bandwidth; radio relay system; dual-band antenna system; linear polarization; dual polarization; quadruplexer

Döhr, P.; Hartwich, H.; Leupelt, U. **SIEMENS**

Antennas and Waveguide Components for Radio Relay Systems

9 figures, 2 tables, 6 references

telcom report 10 (1987) Special "Radio Communication," pp. 136 to 142

The introduction of new radio relay systems, and in particular the transition from analog to digital techniques, has imposed increasingly stringent requirements on the electrical properties of the antennas employed. The simple parabolic or shell-type antennas used up to this time were not capable of optimally meeting these requirements. Furthermore, the demand for a more tightly meshed network, which at present consists of routes operated exclusively with two orthogonal linear polarizations, as well as the increasing problems of installation space on radio relay towers have led to new solutions.

Descriptors: radio relay system; parabolic antenna; shell-type antenna; co-polarization; cross-polarization; waveguide; SIRAL®

Steinkamp, J.; Ulmer, W. **SIEMENS**

The Spectrum of Analog Radio Relay Systems

8 figures, 3 tables, 23 references

telcom report 10 (1987) Special "Radio Communication," pp. 157 to 166

Analog radio relay networks based on radio relay systems employing frequency modulation have remained an essential component in communications throughout the world. A varied range of equipment and systems has been developed for such networks and is presented in this article.

Descriptors: analog radio relay system; long-haul network; medium-haul network; direct and indirect modulation; narrowband system; wideband system; antenna; branching filter; SIRAL® waveguide; protection switching; power supply

Löw, W. **SIEMENS**

Low-loss Feeder for Radio Relay and Radar Systems

5 figures, 2 tables, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 143 to 146

SIRAL® waveguides can be used above their single-mode range when a special mode filter is used. This provides a substantial reduction in losses in comparison with other waveguides. For example, the line loss in the frequency range between 10 and 15.4 GHz is reduced by more than two thirds. This article additionally describes possible applications in other frequency ranges and considers the limits of applicability of this type of line.

Descriptors: SIRAL® waveguide; mode filter; feeder loss; single-mode limit

Barth, H.; Bayer, Th.; Simon, J. **SIEMENS**

Protection and Program Switching Equipment for Analog Radio Relay Links and Networks

7 figures, 2 tables, 5 references

telcom report 10 (1987) Special "Radio Communication," pp. 166 to 172

Automatic protection switching equipment helps to increase the overall availability of radio relay links. In addition, program switching equipment is used in radio relay networks in order to switch the unidirectional routes. A versatile, modular range of equipment has been developed for automatic protection and program switching in analog radio relay links and networks.

Descriptors: analog radio relay link; protection switching equipment; program switching equipment; availability; network protection switching; switching system

Hecker W.; Peterknecht, K.; Scholz, J. **SIEMENS**

Radio Relay Systems FM-TV/2200 and FM-TV/3500 for Television Program Transmission

7 figures, 1 table, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 173 to 177

The increasing demand for radio frequencies for new digital radio relay transmissions and the expansion of TV transmission capacities in the Federal Republic of Germany have led to the development of two new radio relay systems in the frequency bands, 2.1 to 2.3 and 3.4 to 3.6 GHz. Both systems have been designed to provide compatibility with existing analog TV transmission equipment.

Descriptors: FM-TV/2200 radio relay system; FM-TV 3500 radio relay system; radio-frequency band

Gold, R.; Schwinghammer, H. **SIEMENS**

Project Planning and Surveying of Communication Networks

8 figures, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 195 to 202

Project planning for communication networks is assuming increasing importance because of the growing attention that has to be paid to local and national conditions as well as reliability and economy. Siemens, with its experience gained from completed projects and its transmission system know-how, is well qualified to plan projects to clients' requirements.

Descriptors: communication network; survey; project planning; network structure; survey method; survey equipment

Eichhorn, P.; Kübler K.; Pascher, H. **SIEMENS**

Self-Contained Power Supply Systems

11 figures, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 179 to 184

When setting up radio relay transmission links there is often no commercial power network available to power the repeater stations. It is then necessary to provide a self-contained power supply adapted to conditions in the particular country. For high power requirements, dual or triple diesel power plants are installed with rectifiers and batteries. Stations with difficult access or low power requirement are operated from solar and wind energy.

Descriptors: self-contained power supply; radio relay repeater station; wind power plant, solar power plant; diesel power plant; shelter with passive cooling system

Brubach, B.; Glaue, M. **SIEMENS**

Project Management for Communications Engineering Projects Abroad

5 figures

telcom report 10 (1987) Special "Radio Communication," pp. 203 to 207

For large-scale projects, particularly those on a turnkey basis, the creation of a project organization tailored to the requirements of a particular project is just as important as precise project planning at the technical level. Drawing on experience gained in recent major projects, the authors focus on such topics as *organizational structure, personnel, administration,* economical project execution and *flexibility* in coping with national differences.

Descriptors: project management; projects abroad; project organization; project execution; management planning; project management team

Hofmann, S.; Rendl, A. **SIEMENS**

Designing Highly Reliable DC Power Supply Systems for Radio Relay Stations

8 figures

telcom report 10 (1987) Special "Radio Communication," pp. 185 to 189

A reliable and continuously available power supply is essential for the trouble-free operation of radio relay stations. Although the transmission systems are able to handle relatively large voltage variations, the batteries require closely toleranced supply voltages. Regulated rectifiers are required to ensure that variations in the voltage and frequency of the ac supply and other disturbing influences do not affect the dc side.

Descriptors: power supply for radio relay stations; no-break dc power supply; distribution equipment; "radio dc distributor"; lightning protection

Böttner, U.; Lorber, H.-P.; Zscherpe, E.-C. **SIEMENS**

Path and Frequency Planning for Radio Relay Networks

12 figures, 6 references

telcom report 10 (1987) Special "Radio Communication," pp. 208 to 215

The specified transmission quality and the availability of a radio relay network can only be achieved by giving detailed consideration to the effects of routing, climate, topography, frequency band and equipment. In view of the multiplicity of factors which have to be taken into account, it is advisable to adopt an iterative approach in the path and frequency planning process. The authors describe the step-by-step, computer-based approach in a project planning context.

Descriptors: radio relay network; frequency planning; path planning; wave propagation; routing; diversity reception; space diversity; frequency diversity

Boch, B.; Hofmann, S. **SIEMENS**

No-Break AC Power Supply for Earth Stations

7 figures

telcom report 10 (1987) Special "Radio Communication," pp. 190 to 193

Power supply systems for earth stations are subject to stringent reliability requirements. They are usually located remotely from the communication systems and furnish the loads with a secure ac supply via special feeders. This paper discusses the configuration of a state-of-the-art power supply system for an earth station.

Descriptors: power supply system for Intelsat earth station; no-break ac power supply; standby ac power plant; power switchboard; ac distribution; static bypass switch

Bocquet, Ch.; Zscherpe, E.-C. **SIEMENS**

Planning for Optimum Radio Coverage in Mobile Radio Networks

6 figures, 8 references

telcom report 10 (1987) Special "Radio Communication," pp. 216 to 220

In a way similar to television and radio broadcasting, a public mobile radio system must provide adequate field strength for trouble-free reception to guarantee accessibility of mobile users throughout the entire service area. A central feature of the planning of mobile radio networks is the calculation of this radio coverage. The article describes a procedure, by means of which the contours representing the topography can be stored and processed in a computer.

Descriptors: radio coverage; path profile; mobile radio; received field strength; propagation model

Schreiner, G.; Stumme, D. **SIEMENS**

Project Planning and Construction of Earth Stations

8 figures, 6 references

telcom report 10 (1987) Special "Radio Communication," pp. 221 to 228

Siemens has constructed a number of earth stations for satellite communication both at home and abroad. The operations involved from the preparatory planning stage through to handover of the operational system to the client are described with reference to an Intelsat Standard A earth station. The earth stations constructed in accordance with the procedure described are noted for their future-oriented technology and high reliability.

Descriptors: project planning for earth stations; construction of large antenna systems; Intelsat Standard A station

Bulst, W.-E.; Willibald-Riha, E. **SIEMENS**

Reproducible Fabrication of Surface Acoustic Wave Filters

6 figures, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 247 to 252

In the frequency range, 10 MHz to 1 GHz, surface acoustic wave (SAW) filters are established components in radio transmission systems. They provide a high degree of design flexibility, permitting a wide range of applications in miniaturized, monolithic delay lines, filters and correlators. The great success of SAW technology is attributable to ultraprecision fabrication of these devices by photolithographic techniques.

Descriptors: surface acoustic wave; SAW filter; photocomposition process; liftoff technique; etching; piezoelectric substrate; photolithography; reproducibility

Becker, J.; Schreiner, G. **SIEMENS**

Planning and Commissioning of Mobile Radio Systems

4 figures, 4 references

telcom report 10 (1987) Special "Radio Communication" pp. 228 to 233

The digitally-controlled C450 mobile radio system is technologically one of the most advanced telecommunication transmission systems. For this reason, new methods had to be employed for the planning and commissioning. General planning criteria, radio propagation measurement and the demands made upon the planning of the C450 mobile radio system, and its commissioning are described.

Descriptors: C450 mobile radio system; planning; commissioning; planning criteria; radio propagation measurement; radio system measurement; software function test; interface test; system function test

Grassl, H.-P. **SIEMENS**

Surface Acoustic Wave Convolvers for Spread Spectrum Radio Systems

12 figures, 7 references

telcom report 10 (1987) Special "Radio Communication," pp. 253 to 259

Efforts to increase the interference protection for radio transmissions lead to the use of wideband modulation methods such as the spread spectrum technique. Signals encoded in this process are decoded using surface acoustic wave (SAW) convolvers. The author discusses the principle of correlation detection of coded signals in spread spectrum systems and describes the operation and design of a SAW convolver.

Descriptors: wideband modulation; spread spectrum technique; surface acoustic wave technology; convolver; interdigital transducer

Hoffmann, R.K. **SIEMENS**

Technology and Design of Microwave Components

9 figures, 1 table, 5 references

telcom report 10 (1987) Special "Radio Communication," pp. 235 to 241

For more than a decade many of the microwave components used in radio relay, satellite and mobile radio equipment have been designed mainly in hybrid microwave integrated circuit technology. This technology permits economical manufacture and a high level of computer support in designing complex components in the frequency range from about 1 GHz to beyond 20 GHz.

Descriptors: microwave component; hybrid microwave integrated circuit; MIC device; substrate; microstrip; thin-film technology; thick-film technology; CAD tools

Gernegross, D.; Kahn, K.-D. **SIEMENS**

Designing Semi-Custom Integrated Circuits

4 figures, 5 references

telcom report 10 (1987) Special "Radio Communication," pp. 259 to 263

The use of semi-custom integrated circuits in *digital* radio relay transmission equipment offers considerable advantages, such as compactness, lower power dissipation and higher reliability. As a result of these improvements, it has been possible to develop equipment which could not have been realized using standard circuits – e.g. low power designs, equipment with complex signal processing functions or large transmission capacities.

Descriptors: digital radio relay system; semi-custom integrated circuit; standard cell; VLSI development system

Riha, G.; Stocker, H.; Zibis, P. **SIEMENS**

Surface Acoustic Wave Filters for Digital Radio Relay Systems

13 figures, 5 references

telcom report 10 (1987) Special "Radio Communication," pp. 241 to 246

Surface acoustic waves (SAW) can be used to provide customized transfer functions of unprecedented precision and filters of incomparably high Q. They are therefore employed in digital radio relay systems as spectrum-shaping IF filters, as delay lines in voltage-controlled oscillators and as resonators in oscillators for frequency-conversion.

Descriptors: surface acoustic wave (SAW); digital radio relay systems; spectrum-shaping filter; voltage-controlled oscillator; frequency conversion

Wilhelm, W. **SIEMENS**

Bipolar Technology for Semi-Custom ICs in High Data Rate Transmission Systems

8 figures, 2 tables, 5 references

telcom report 10 (1987) Special "Radio Communication," pp. 263 to 267

The SH100B and SH100C are gate array families available for applications in digital transmission systems. The first category of these large-scale integrated circuits provides complexities ranging up to 900 gate functions with a gate delay of 0.5 ns, the second category up to 2500 gate functions and a gate delay of 0.35 ns.

Descriptors: bipolar technology; semi-custom integrated circuit; high data rate digital transmission system; SH100C gate-array family; SH100B gate-array family; large-scale integrated circuit; gate function; gate delay

Gosslau, K.; Wallner, J. **SIEMENS**

Systematic Quality Assurance

4 figures, 1 table, 10 references

telcom report 10 (1987) Special "Radio Communication," pp. 269 to 273

Siemens develops, manufactures, markets and sells a wide range of high-quality products – from microelectronic components to large systems with the associated software and services. As quality is a vital factor in Siemens' business policy, all functional areas are actively involved in the important task of quality assurance. Supported by an effective quality assurance system, the Planning, Sales and Marketing, Development, Production, Installation and Customer Service departments work in close cooperation.

Descriptors: quality assurance system; product quality; quality assurance manual; quality assurance plan

Elster, K.-J.; Mangelsdorf, D.; Zscherpe, E.-C. **SIEMENS**

Product Quality and Quality Assurance Right from the Start

12 figures, 7 references

telcom report 10 (1987) Special "Radio Communication," pp. 273 to 280

Communication equipment must operate reliably and with minimum interference, often under extreme climatic conditions. Consequently the highest quality assurance standards must be applied right from the design phase, in component selection as well as module and unit design. This article describes the comprehensive product-related quality assurance concept.

Descriptors: quality assurance; component testing; standardization; circuit design; reliability prediction; component qualification; stress limit; thermal characteristics; electromagnetic compatibility

Zefferer, G. **SIEMENS**

Quality Assurance in the Development of Software for the C450 Mobile Radio System

3 figures, 4 references

telcom report 10 (1987) Special "Radio Communication," pp. 281 to 284

The quality assurance measures employed in the development of the C450 mobile radio system are described with reference to the software for the base station. The main aspects of quality control – conventions, product and project structuring, and planning and control – are highlighted. Based on these aspects the author also discusses the development process with its stage-by-stage quality assurance.

Descriptors: C450 mobile radio system; base station; software development; quality assurance; product structure; project structure; planning

Hadersdorfer, L. **SIEMENS**

Quality Assurance in the Radio Production Facility

3 figures, 2 references

telcom report 10 (1987) Special "Radio Communication," pp. 285 to 287

One of the basic requirements for any production operation is to manufacture products of consistent quality at competitive cost. It is the function of quality assurance to ensure that a product possesses the desired quality characteristics. In this article, the author discusses the quality assurance concept adopted in the Radio Production Facility in Munich, and describes the various stages of quality assurance from receiving, parts production and assembly through to final testing. Another important activity described is the regular checking and calibration of all measuring and test equipment.

Descriptors: quality assurance; AQL (acceptable quality level) values; inspection; testing program calibration

"Mobile Communication" is the first in a series of *telcom report Specials* dealing with radio communication. Cellular radio networks now in operation, and capable of handling several hundred thousand mobile users, represent a significant expansion of telephone service and increase in user comfort. Authored by Siemens' experts, "Mobile Communication" documents cellular radio technology realized in the C450 network.

Topics:
- Design of cellular networks
- Cellular service in urban areas
- Relative distance measurement
- Radio transmission
- Signaling transmission
- Mobile station accessibility
- Handoff procedures
- Call processing functions
- Network synchronism
- Software functions
- O & M
- Safeguarding
- Base station design
- Mobile station design

telcom report Special
"Mobile Communication"
Volume 9, November 1986
Order No. A19100-L523-V854-X-7600
ISBN 3-8009-3854-5

The second *telcom report Special* on topics from the field of radio communication, "Components for HF Networks," describes the technologies and components in modern HF radio networks. Because of the considerable progress brought about by new technologies, strategic and tactical HF networks are increasingly regaining importance. "Components for HF Networks" portrays the state-of-the-art of such networks.

Topics:
- ECM-resistant communication
- Control and supervision
- Automatic error correction
- 2400 bit/s modem
- Versatile communication processor
- Advanced radio relay systems

telcom report Special
"Components for HF Networks"
Volume 10, January 1987
Order No. A19100-L523-V855-X-7600

"Satellite Communication," the third *telcom report Special* on radio communication topics, examines the many aspects of transmission in satellite systems. Following a review of satellite communication systems in general and a discussion of the main access methods for satellite networks, "Satellite Communication" describes the components implemented, beginning with earth stations – from the large Standard A earth stations for the Intelsat system to smaller earth stations used in national networks. Emphasis is then placed on technologies employed in earth stations. Finally, a system for the remote monitoring and control of earth stations in national networks is introduced.

Topics:
- Satellite communication systems
- Access methods for satellites
- Standard A earth stations
- National satellite communication
- Network access systems for "new services"
- Antennas and feed systems
- Traveling-wave tube amplifiers
- Up-converters
- Adjustable equalizer modules
- Remote control system

telcom report Special
"Satellite Communication"
Volume 10, April 1987
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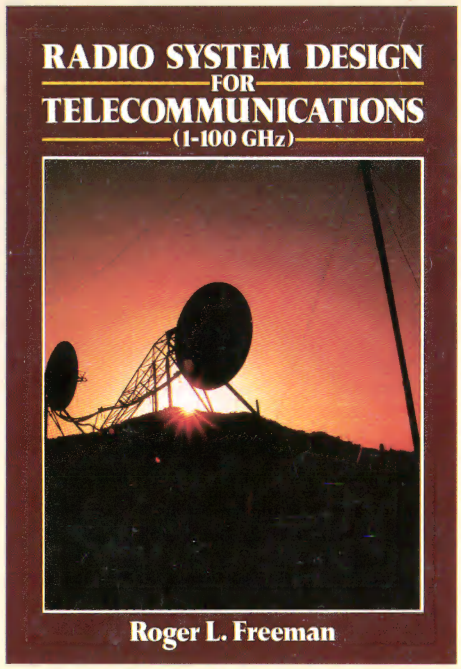

Radio System Design for Telecommunications (1–100 GHz)

by Roger L. Freeman

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This definitive resource describes how radiolinks operate, how to size or dimension terminals and ancillary subsystems, and how to select the necessary performance parameters and equipment specifications to meet the needs of various customers. Chapter 1 features a general review of the mechanisms of radio propagation in free space, over obstacles, and in the earth's atmosphere. Chapter 2 covers the essential design principles of broadband radio communication links – where the transmitting antenna on one end and the receiving antenna on the other are within "line-of-sight" of each other. LOS radio links have the broadest application for point-to-point multichannel communications and video transmission and are the most widely implemented of all the radio disciplines covered in this book. Chapter 3 provides design techniques for over-the-horizon radio links. Stressing tropospheric scatter, it also covers single-obstacle and smooth-earth diffraction paths. Subsequent chapters cover the design and dimensioning of satellite earth stations with respect to geostationary satellites, discuss propagation and system impairments (especially noise and intersymbol interference) as well as link design and equipment sizing, and deal with digital systems and processing satellites. Covering both LOS radio links and satellite systems, the book also treats such topics as excess attenuation and noise due to rainfall, depolarization, excess attenuation due to gaseous absorption, and mitigation techniques available to meet performance requirements such as implicit, explicit and spatial or path diversity. It also deals with modulation waveform selection, bit packing and coding/decoding techniques.

Tables, figures, and equations make even the most complex material more accessible to both practicing engineers and students. The book is rich with sample problems leading the reader step by step through the system design process. *Radio System Design for Telecommunications (1–100 GHz)* is a valuable working tool for those involved with designing radio systems at every level.

Step by step, *Radio System Design for Telecommunications (1–100 GHz)* explains how to plan, engineer and design analog and digital radio links in the point-to-point telecommunications service. It covers every aspect of radio system design used in telecommunications – including siting criteria, hardware layout, performance predictions, links and system analysis, facility planning and frequency assignment information.

Contents of the book

- Radio propagation 1–100 GHz
- Line-of-sight radiolinks
- Over-the-horizon radiolinks
- Basic principles of satellite communication – analog syst
- Digital communications by sa
- System design above 10 GHz
- Radio terminal design – A system approach

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